

Concrete Repair and Maintenance Illustrated

- *Problem Analysis*
- *Repair Strategy*
- *Techniques*

Peter H. Emmons



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- Problem Analysis
- Repair Strategy
- Techniques

Peter H. Emmons

Here is the tool you need to clearly understand and successfully carry out concrete repair and maintenance projects—with confidence! In this book you will find a detailed, yet concise presentation of over 220 concrete repair and maintenance topics. Issues are examined within the framework of analysis, strategy development, and repair techniques, with extensive and superbly detailed illustrations to guide you in the proper planning and execution of repairs.

Written by Peter H. Emmons, President of Structural Preservation Systems, Inc., and a national authority on concrete repair, *Concrete Repair and Maintenance, Illustrated* was technically reviewed and edited by James Warner, world-renowned concrete repair consultant and educator, and Alexander M. Vaysburd, Ph.D., an expert in concrete technology with more than 30 years experience in the industry.

This indispensable book provides extensive information about problem analysis, strategy development, engineering aspects, material criteria, and repair and maintenance methods. Designed for ease of use by all participants in the repair and maintenance process—owners and facilities managers, engineers, architects, material suppliers and contractors—the book's unique format provides a highly structured, fully illustrated examination of each topic.



Peter H. Emmons

Concrete Repair and Maintenance Illustrated

This comprehensive instructional reference includes detailed information on:

- Concrete Behavior
- Evaluating Concrete Problems
- Surface Repair
- Stabilization and Strengthening
- Protection

Dedicated to quality assurance and technical excellence, the author provides the concrete repair industry with a much-needed reference guide designed to facilitate adherence to the highest standards in the design and execution of concrete repair and maintenance projects.

About the Author

Peter H. Emmons is President of Structural Preservation Systems, Inc., the nation's largest dedicated concrete repair contractor, headquartered in Baltimore, MD. Mr. Emmons holds a B.S. degree in Civil Engineering from the University of Maryland, has over twenty years experience in structural concrete repair, and has been involved with over 3,000 concrete repair projects. He is the author of several widely distributed publications, including *The Guidebook for Repair and Maintenance of Parking Structures* (1988), and the highly respected quarterly publication, *Repair Techniques* (1989). He is noted for his articles and presentations addressing topics such as the importance of drying shrinkage values in the selection of repair materials, and innovative techniques for the repair of post-tensioned structures, as well as for development of a patented waterstop repair system which has filled a critical need in the repair of leaking waterstops.

Mr. Emmons provides industry leadership through the International Association of Concrete Repair Specialists (IACRS), serving as a member of the Board of Directors and as chairman of the Technical Guideline Committee, which produced the first industry guidelines for concrete removal around exposed reinforcing steel. He is also a member of both the 546 Repair Committee and the 364 Rehabilitation Committee of the American Concrete Institute (ACI).

Mr. Emmons is committed to fostering the development of a much-needed strategic alliance between contractor, engineer, supplier, and owner to successfully address the complex, interactive requirements of effective concrete repairs.

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To all employees of Structural Preservation Systems, Inc.
and all past, present and future clients.

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Introduction

Concrete repair is a complex process, presenting unique challenges very different from those experienced in the field of new concrete construction. Concrete repair must successfully integrate new materials with old materials, forming a composite capable of enduring the exposures of use, the environment, and time.

Concrete repair, which began with the first concrete placement, came of age as the nineteen sixties, seventies, and eighties produced a proliferation of concrete structures. Today, concrete repair is a major industry supporting the needs of virtually every concrete structure. Each structure requires routine repair and maintenance, ranging from simple protective coatings to repair of spalling concrete to strengthening of under-designed components. With the growth of any marketplace come new players eager to participate. In the concrete repair business, this includes contractors, engineers, architects, and material suppliers. What newcomers find is an industry in need of technical definition and guidelines for standard practice—the lack of which can lead to poorly designed repairs, ill-conceived materials, and poorly executed field procedures. All too often, the results are premature repair failures.

The purpose of this book is to present concrete repair as an integrative process of analysis, strategy, and technique, relating concrete behavior directly to the field repair process. The author stresses the critical importance of continuity between engineering, materials, and technique, as well as the need for sound technical knowledge and effective communication within the project team. The book raises questions and provides ideas for solutions.

The dynamics of new materials interacting with in-place materials is still an emerging science. Enhanced methods of analysis, improved strategies and techniques and new materials will facilitate quality growth of the concrete repair industry. This book is designed to guide and support that growth through its emphasis on the practices of quality analysis, careful strategy development, and proper selection of technique and materials.

The book presents the philosophy that owners, engineers, material suppliers, and contractors all need to understand the basics of each discipline represented in the repair process. The contractor must understand concrete deterioration mechanisms in order to understand surface preparation. The engineer must understand material behavior, including both physical cured properties and the chemical uncured behavior, in order to properly specify a successful repair material. The manufacturer of repair materials must not only apply sound chemical principles, but also understand the engineering aspects of how repair materials will interact with an existing substrate under load carrying conditions. The owner must be a generalist familiar with concrete problems and potential solutions.

The book's style of delivery is intended to support the purposes, philosophy, and needs outlined above, using easily understood graphics with explanatory text. Wherever possible, each topic is contained on one page, presenting an inclusive unit of information. Each page contains illustrations designed to help the reader visualize a particular mechanism or strategy.

Many of the author's experiences, including failure experiences, are used as case studies. Understanding what to avoid can be the most valuable information gained from reading this book. The use of flow charts throughout the book provides continuity between pages and sections. Metric conversions are shown for most English units. The book is designed to be easily understood by all who participate in the process of concrete repair and maintenance.

The book has been organized in a fashion similar to the progression of steps found in a typical repair project. It begins with an extensive discussion of concrete behavior, addressing elements which may lead to defects, deterioration or damage. The section that follows addresses evaluation techniques commonly used to analyze the behavior and establish the general

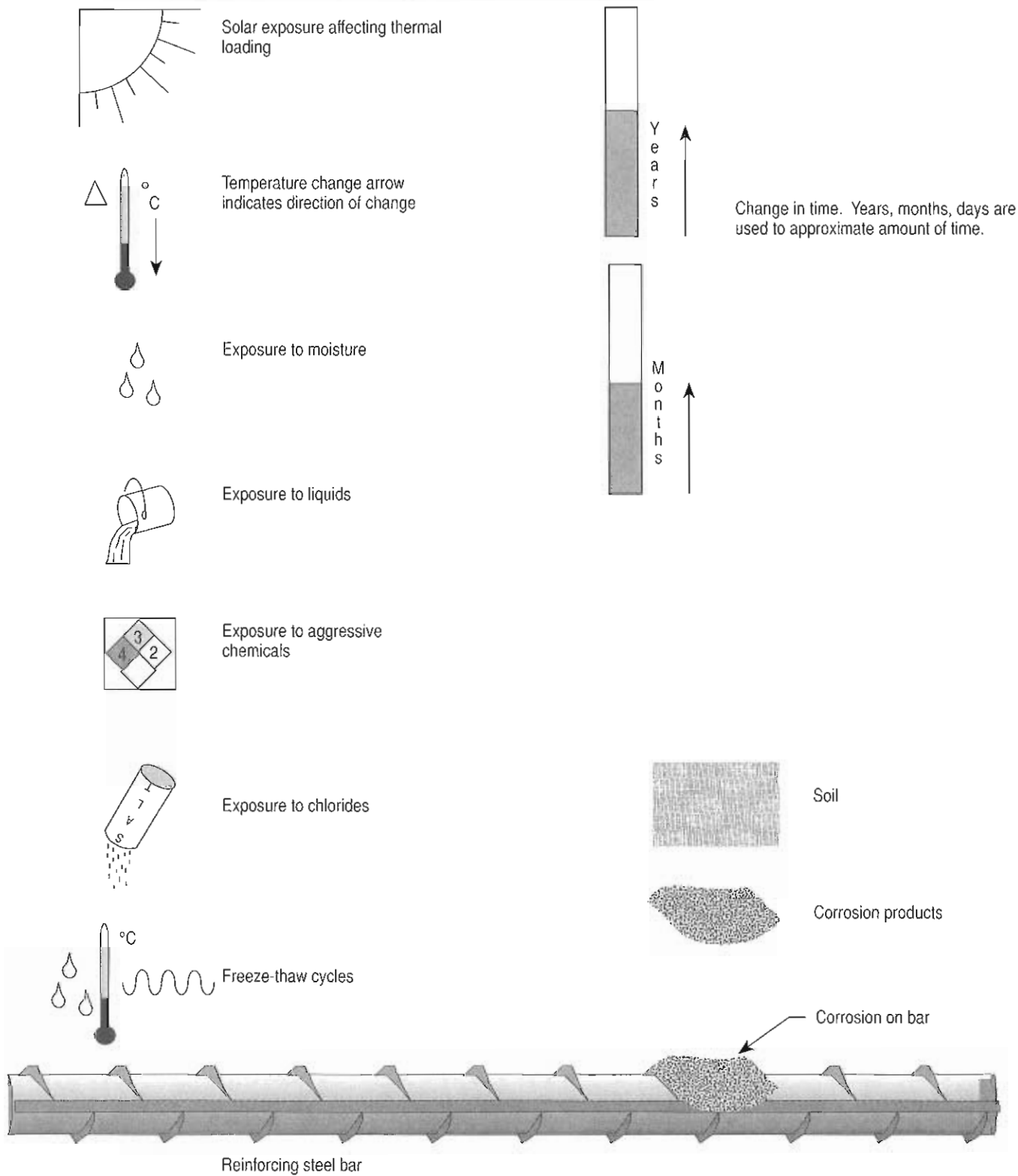
scope of defects. Parts Three, Four, and Five of the book deal with the strategy and techniques necessary to repair and maintain a particular structure or member. Part Three "Surface Repair," is the most comprehensive, including a discussion of engineering aspects, material requirements, surface preparation and material placement techniques. Part Four "Stabilization and Strengthening," includes discussion of various techniques to stabilize or strengthen a member or structure. The discussion is oriented towards ideas for possible solutions. Part Five "Protection," is a broad category including techniques and strategies for waterproofing, and barriers to unwanted exposure or service conditions.

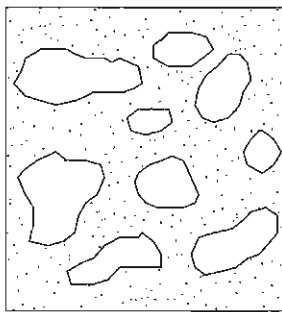
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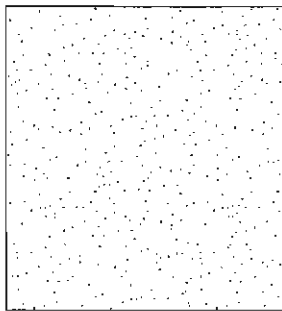
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Symbols

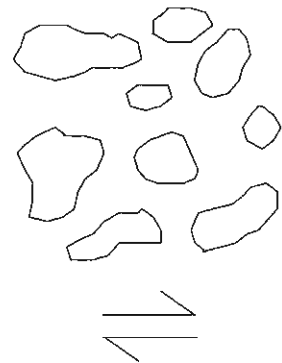




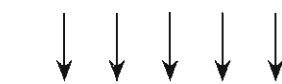
Concrete



Concrete



Large aggregate



Applied loads



Compression



Tension



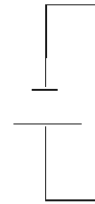
a change resulting in decrease



a change resulting in increase



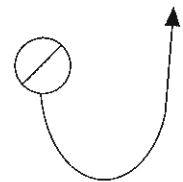
Use caution, unclear as to right answer.



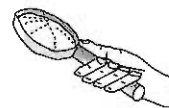
Electrical power source



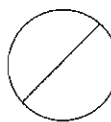
Barrier to exposure or service conditions



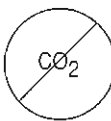
Closeup view



Penetration or movement



Identifies a wrong approach to a particular problem



Barrier to the exposure specified within the symbol

What You Need To Know Before Using This Book

The book uses extensive references to publications of the American Concrete Institute (ACI). Much of the technical knowledge available about repair is contained in the five-volume *ACI Manual of Concrete Practice*. For more information about ACI, write: American Concrete Institute, P.O. Box 19150, Redford Station, Detroit, Michigan 48219. Other sources of information include:

- American Society of Testing and Materials (ASTM)

More information can be obtained by writing:

American Society of Testing and Materials

1916 Race Street

Philadelphia, PA 19103-1187, USA

- International Association of Concrete Repair Specialists (IACRS)

More information can be obtained by writing:

International Association of Concrete Repair Specialists

P.O. Box 17402

Dulles International Airport

Washington, DC 20041

- Additional reading materials to further one's knowledge are referenced at the end of each section.

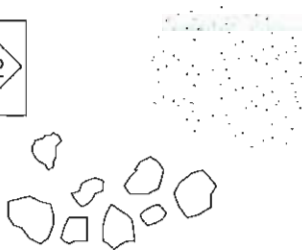
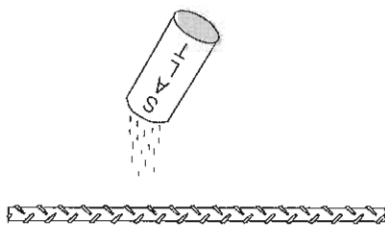
The graphics used in this book utilize symbols representing certain conditions or exposures. A symbol library is provided following the introduction.

Part One
**Concrete
Behavior**

Part One

Concrete

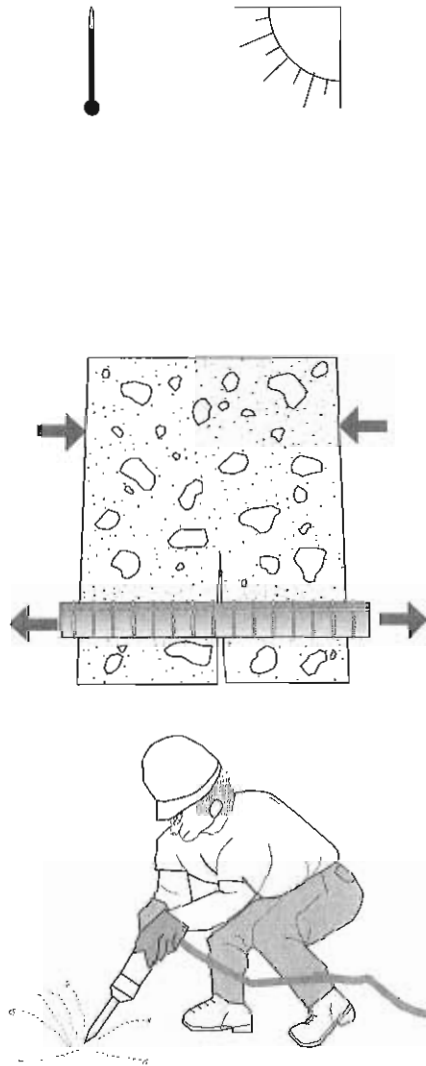
Behavior



Part One

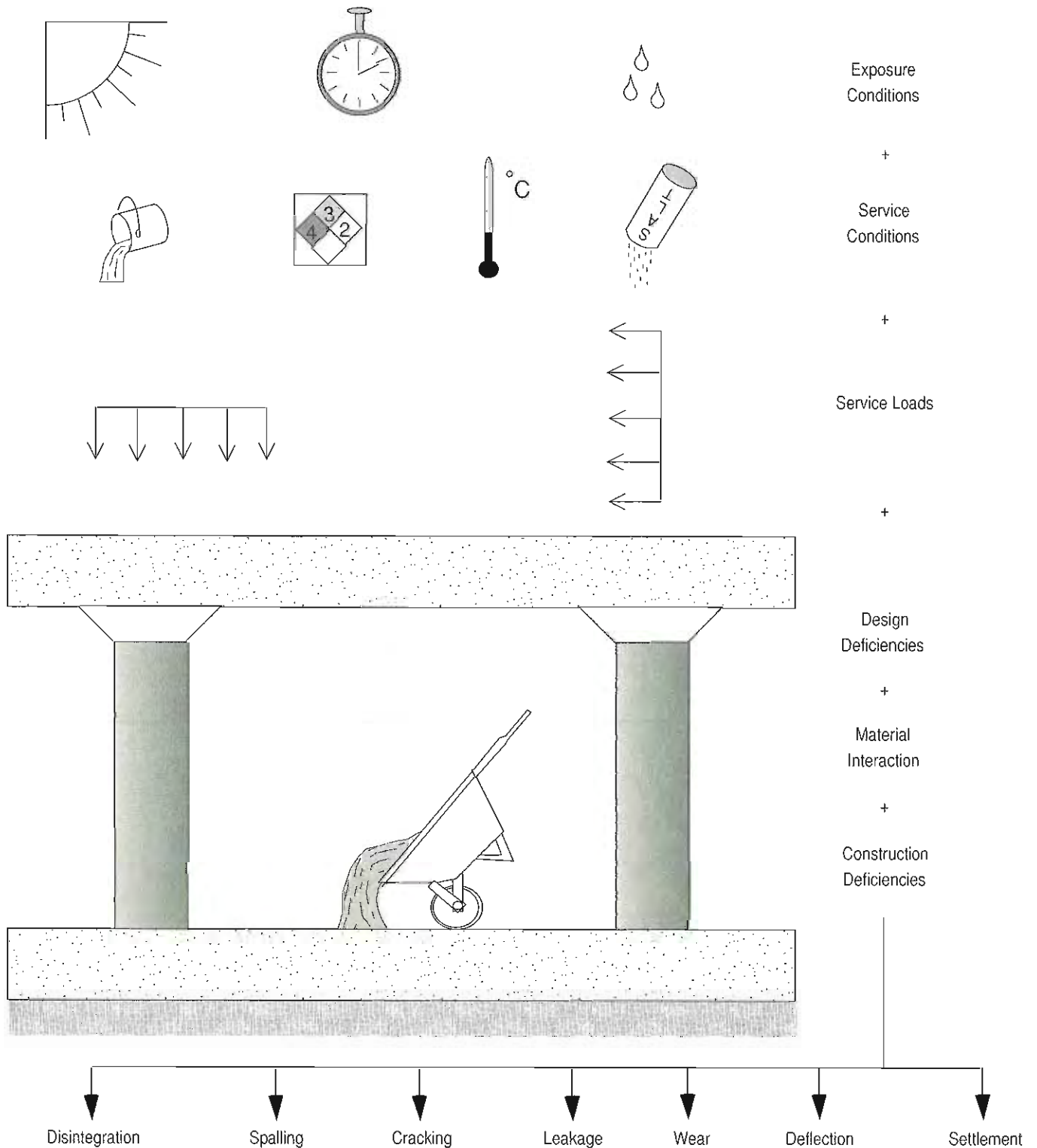
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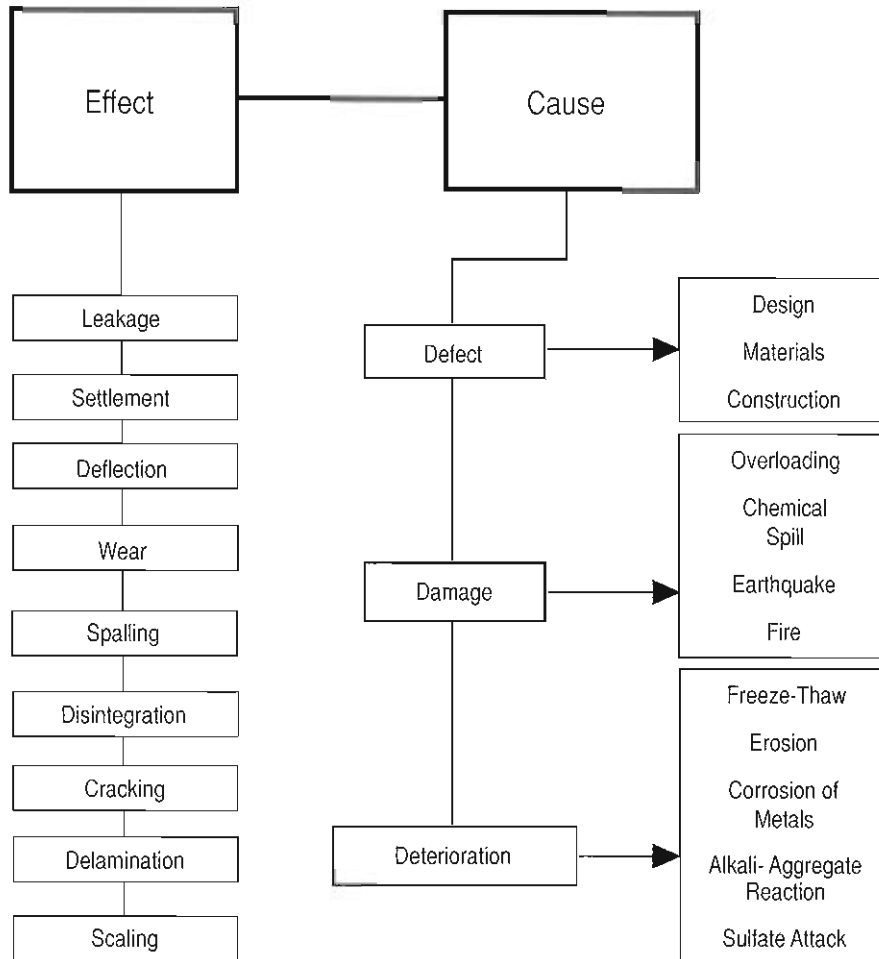


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Introduction



Introduction to Part One



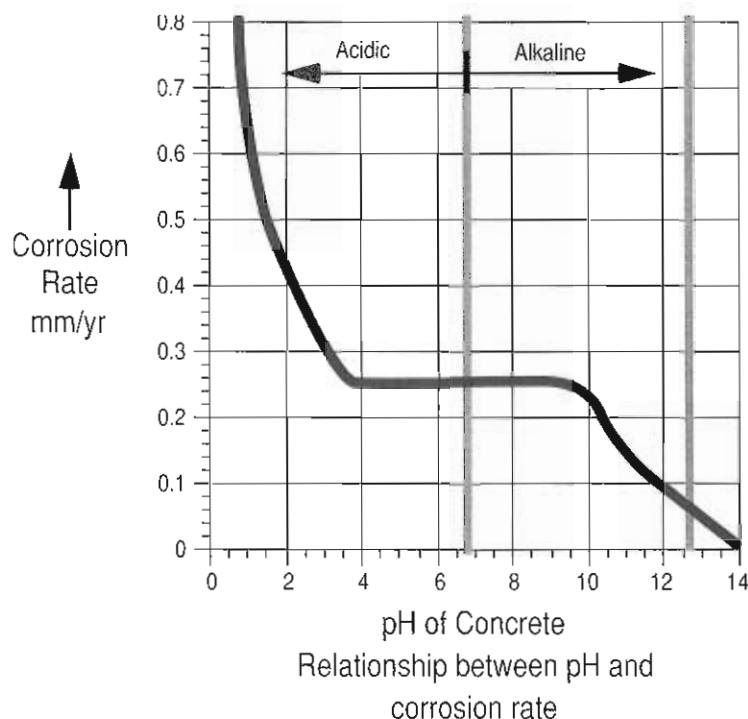
Concrete does not always behave as we would like; some of the undesirable behavior can be seen as disintegration, spalling, cracking, leakage, wear, deflection or settlement. Developing effective repair strategies requires an understanding of what caused the undesirable behavior. Understanding the cause allows the repair strategy to address both the cause and the effect (behavior). The result is a successful, long lasting repair.

A variety of factors influence concrete behavior. These factors include: design, materials, construction, service loads, service conditions and exposure conditions. Most of the observed behaviors are a combination of these factors working together. The discussion of concrete behavior in this section has been subdivided into six categories. The first two categories, Embedded Metal Corrosion and Disintegration, address deterioration mechanisms. The next three, Moisture Effects, Thermal Effects and Load Effects, address exposure and service conditions. The last category addresses defects due to improper workmanship.

- Embedded Metal Corrosion Process
- Corrosion-Induced Spalling
- Reduction in Structural Capacity
- Chloride Penetration
- Cracks and Chlorides
- Cast-in Chlorides
- Carbonation
- Structural Steel Member Corrosion
- Dissimilar Metal Corrosion
- Post-Tension Strand Corrosion



Embedded Metal Corrosion Process



Concrete is a high alkalinity material. The pH of newly produced concrete is usually between 12 and 13. In this range of alkalinity, embedded steel is protected from corrosion by a passivating film bonded to the reinforcing bar surface. However, when the passivating film is disrupted, corrosion may take place.

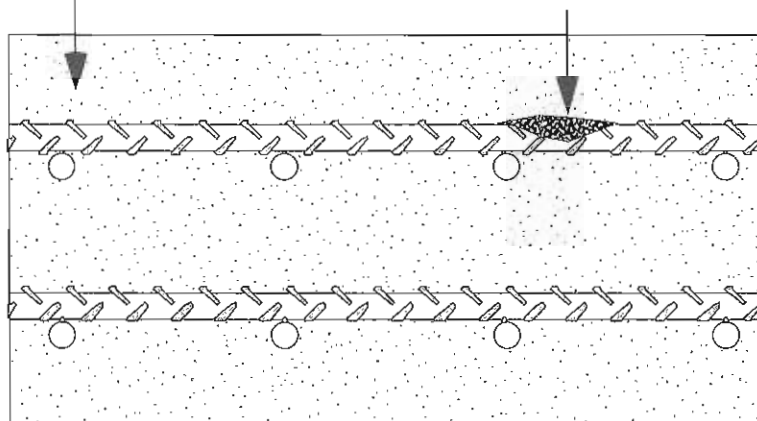
Corrosion is an electrochemical process requiring an anode, a cathode, and an electrolyte. A moist concrete matrix forms an acceptable electrolyte, and the steel reinforcement provides the anode and cathode. Electrical current flows between the cathode and anode, and the reaction results in an increase in metal volume as the Fe (Iron) is oxidized into Fe(OH)_2 and Fe(OH)_3 and precipitates as FeO OH (rust color)¹. Water and oxygen must be present for the reaction to take place. In good quality concrete the corrosion rate will be very slow. Accelerated corrosion will take place if the pH (alkalinity) is lowered (carbonation) or if aggressive chemicals or dissimilar metals are introduced into the concrete. Other causes include stray electrical currents and concentration cells caused by an uneven chemical environment.

Corrosion Inhibitors

High quality concrete
High pH (Alkalinity)
concrete protects
steel surface from
corrosion.

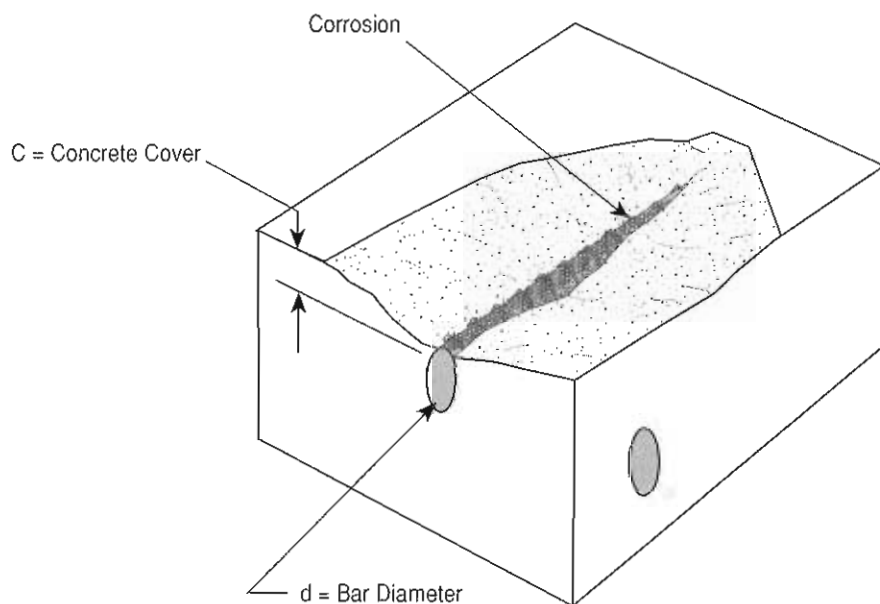
Corrosion Promoters:

- Oxygen
- Water
- Stray electrical currents
- Uneven chemical environment around reinforcement
- Environments that lower the pH (alkalinity)
- Chlorides



¹Clifton, J.R., Predicting the Remaining Service Life of Concrete, National Institute of Standards and Technology Report NISTIR 4712.

Corrosion-Induced Cracking and Spalling



Cracking and spalling of concrete induced by steel corrosion is a function of the following variables:

1. Concrete tensile strength
2. Quality of concrete cover over the reinforcing bar
3. Bond or condition of the interface between the rebar and surrounding concrete
4. Diameter of the reinforcing bar
5. Percentage of corrosion by weight of the reinforcing bar

With a cover-to-bar diameter ratio (C/D) of 7, concrete cracking starts when corrosion reaches 4 percent, whereas, with a C/D ratio of 3, only 1 percent corrosion is enough to crack the concrete¹ (See table below).

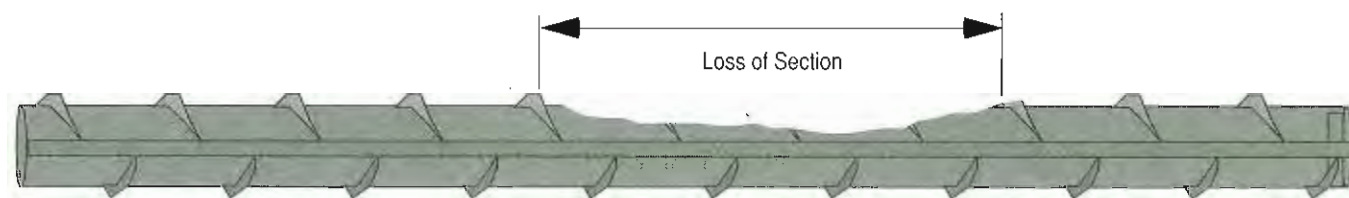
C/D Ratio	Cover in./mm	Bar Size	Corrosion % to Cause Cracking
7	3.5/89	#4	4%
3	1.5/38	#4	1%

¹ Al-Sulaimani, Kaleemullah, Basunbul and Rasheed, "Influence of Corrosion and Cracking on Bond Behavior and Strength of Reinforced Concrete Members," ACI Structural Journal, March-April 1990, p220.

Reduction in Structural Capacity

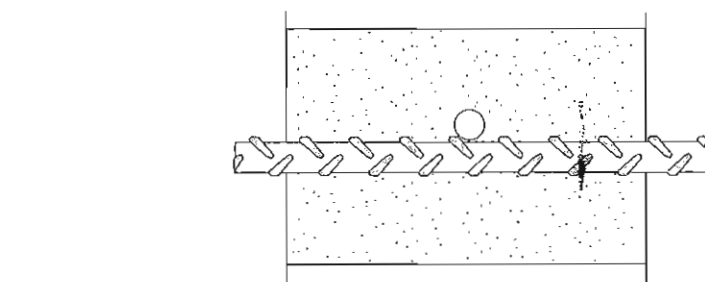
The structural capacity of a concrete member is affected by bar corrosion and cracking of surrounding concrete. The research conducted on flexural beams found that in steel with more than 1.5 percent corrosion, the ultimate load capacity began to fall, and at 4.5 percent corrosion, the ultimate load was reduced by 12 percent—probably a result of reduced bar diameter.¹

It can be surmised that, in compressive members, cracking and spalling of concrete reduces the effective cross section of the concrete, thereby reducing the ultimate compressive load capacity.

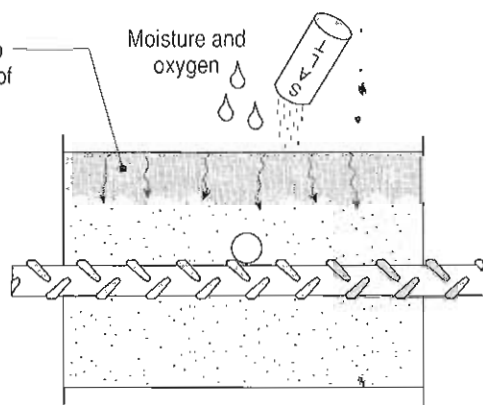


¹Al-Sulaimani, Kaleemullah, Basunbal and Rasheed, "Influence of Corrosion and Cracking on Bond Behavior and Strength of Reinforced Concrete Members," ACI Structural Journal, March-April 1990, p.220.

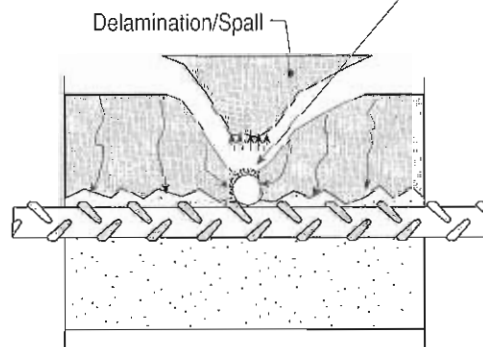
Chloride Penetration



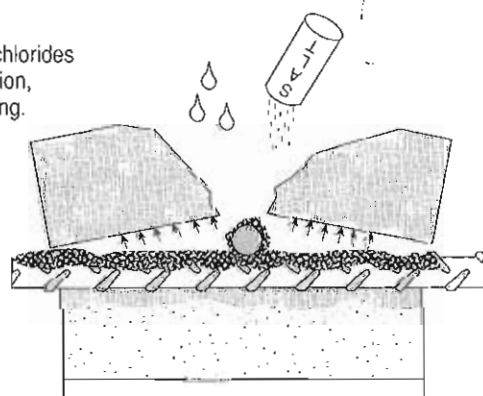
Chlorides penetrate into concrete with the help of surface moisture.



When chlorides penetrate to reinforcing steel corrosion begins.



Further penetration of chlorides results in further corrosion, delamination and spalling.



Chlorides can be introduced into concrete by coming into contact with environments containing chlorides, such as sea water or de-icing salts.

Penetration of the chlorides starts at the surface, then moves inward. Penetration takes time, depending upon:

1. The amount of chlorides coming into contact with the concrete.
2. The permeability of the concrete.
3. The amount of moisture present.

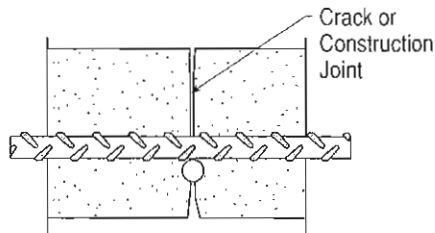
Eventually the concentration of chlorides in contact with the reinforcing steel will cause corrosion when moisture and oxygen are present. As the rust layer builds, tensile forces generated by expansion of the oxide cause the concrete to crack and delaminate.

Spalling of the delamination occurs if the natural forces of gravity or traffic wheel loads act on the loose concrete. When cracking and delamination progress, accelerated corrosion takes place because of easy access of corrosive salts, oxygen, and moisture. Corrosion then begins to affect rebars buried further within the concrete.

The concentration of chlorides necessary to promote corrosion, among other factors, is greatly affected by the concrete's pH. It was demonstrated that a threshold level of 8,000 ppm of chloride ions was required to initiate corrosion when the pH was 13.2. As the pH was lowered to 11.6, corrosion was initiated with only 71 ppm of chloride ions.¹

¹Hausmann, D.A., Steel Corrosion in Concrete, *Materials Protection*, November, 1967, pp. 12-23.

Cracks and Chlorides



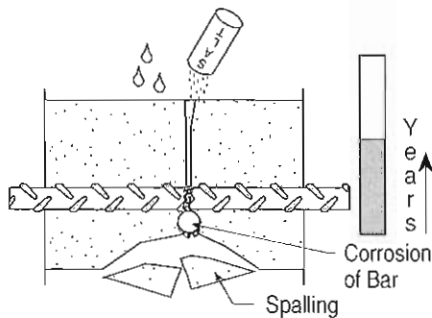
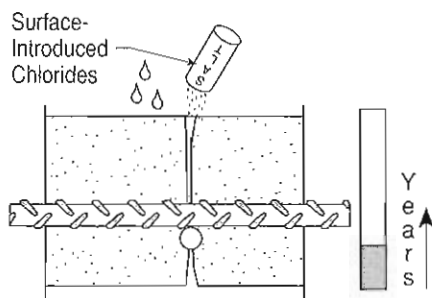
Cracks and construction joints in concrete permit corrosive chemicals such as de-icing salts to enter the concrete and access embedded reinforcing steel.

ACI 224R-90 presents the following table of tolerable crack widths in reinforced concrete:

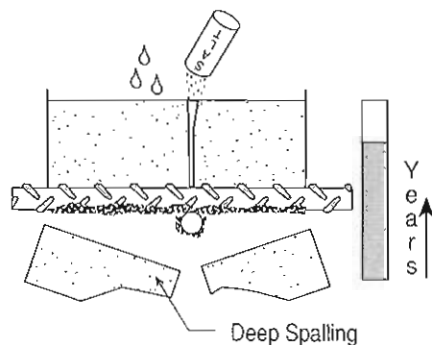
Exposure Condition	Tolerable Crack Width	
	(In.)	(mm)
Dry air, protective membrane	0.016	0.41
Humidity, moist air, soil	0.012	0.30
De-icing chemicals	0.007	0.18
Seawater and seawater spray; wetting and drying	0.006	0.15
Water-retaining structures*	0.004	0.10

*Excluding non pressure pipes.

Note: 0.004 inches is equal to the width of a human hair. A crack of this width is almost unnoticeable unless the surface is wetted and allowed to dry.



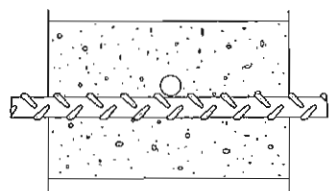
Steel corrosion may take place even in a high alkaline environment if chlorides are present. Chlorides are not consumed in the corrosion process, but instead act as catalysts to the process and remain in the concrete.



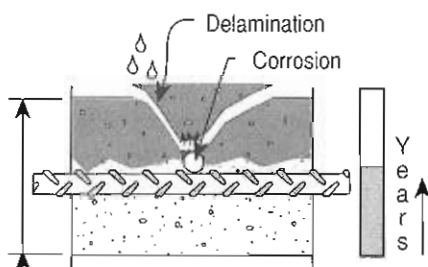
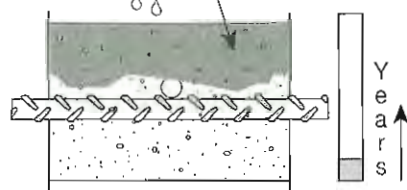
The corrosion process is progressive, beginning at the intersection of the crack with the reinforcing bar, then progressing along the bar.

Cast-in Chlorides

Concrete with Cast-in Water Soluble Chlorides



Note: shaded area denotes level of moisture penetration.



Chloride content is generally the same throughout the cross section.

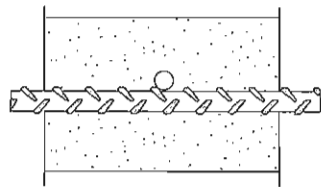
Chlorides can be found in reinforced concrete even before the structure is in service. Chlorides may be introduced deliberately as an accelerator, or in the form of natural ingredients found in some aggregates. Concrete made of beach sand or having seawater for mixing water will result in cast-in chlorides.

Chlorides occur in either water soluble or acid soluble form. Chlorides used as admixtures are water soluble, while those found in aggregate sources may be only acid soluble. Water soluble chlorides are the most damaging, since they readily become free to attack surrounding reinforcing steel.

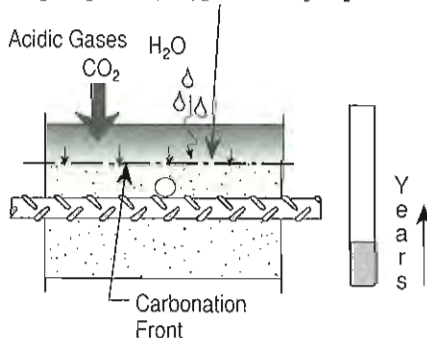
ACI 201.2R suggests the following limits for chloride ion in concrete prior to placing concrete into service:

Service Condition	% of Cl to weight of cement
Prestressed concrete	0.06
Conventionally reinforced concrete in a moist environment and exposed to chloride	0.10
Conventionally reinforced concrete in a moist environment not exposed to chloride	0.15
Above-ground building construction where concrete will stay dry	no limit

Carbonation

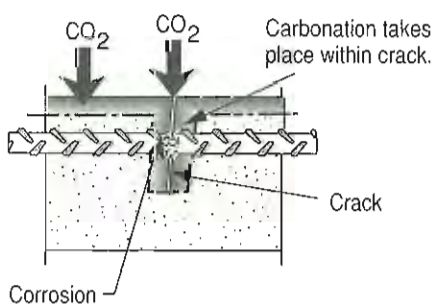
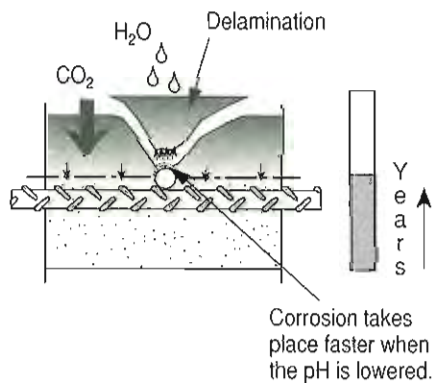


pH is lowered by the reaction . . .
 $\text{CO}_2 + \text{H}_2\text{O} + \text{Ca}(\text{OH})_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}$



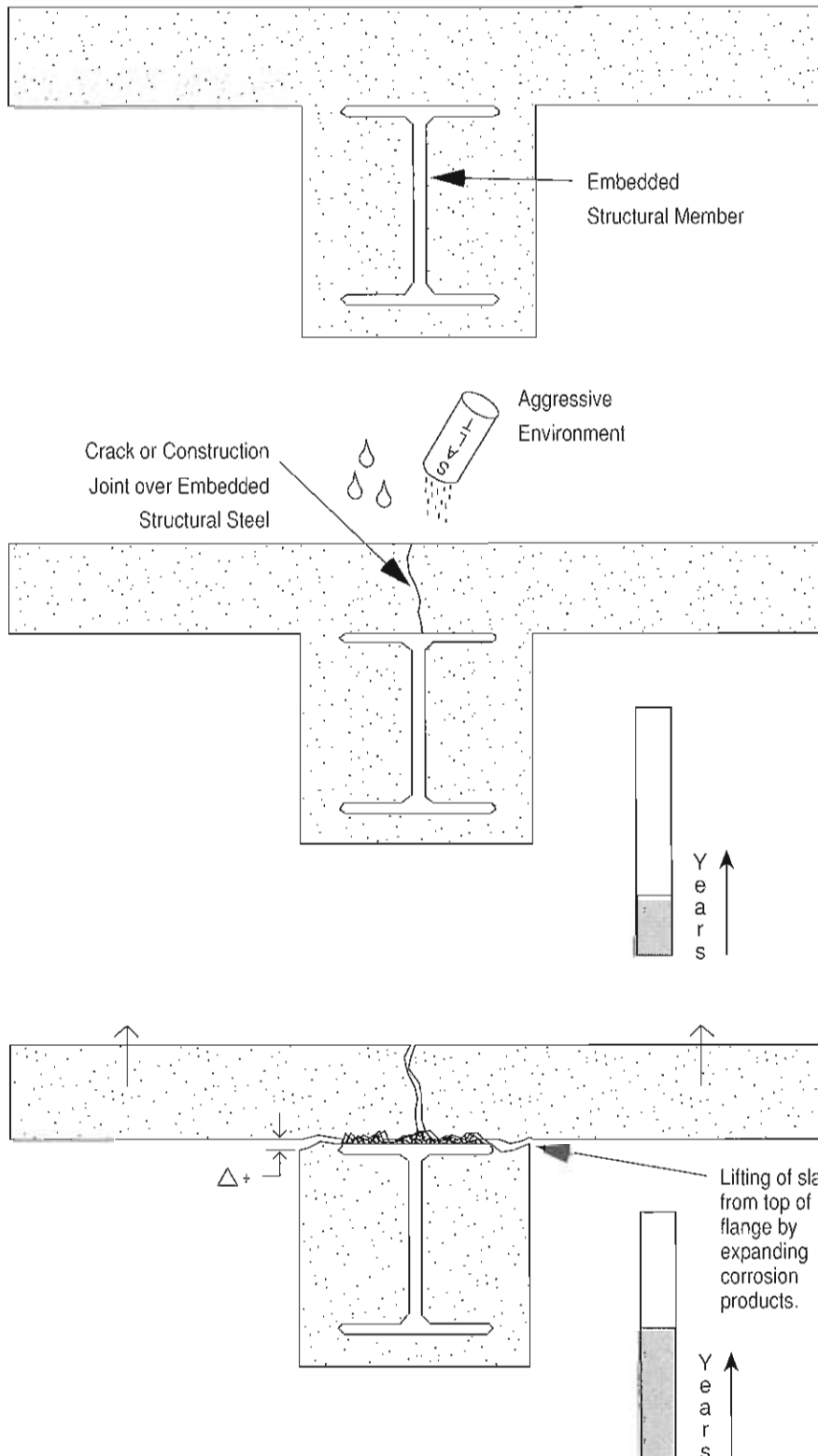
Carbonation of concrete is a reaction between acidic gases in the atmosphere and the products of cement hydration. Normal air contains carbon dioxide (CO_2) in relatively low concentrations (0.03%). The level of carbon dioxide in industrial atmospheres is, as a rule, higher. Carbon dioxide penetrates into the pores of concrete by diffusion and reacts with the calcium hydroxide dissolved in the pore water. As a result of this reaction, the alkalinity of concrete is reduced to a pH value of about 10, and, consequently, concrete protection of the reinforcing steel is lost. The passivity of the protective layer on steel is destroyed. When steel is depassivated and the environment is acidic or mildly alkaline, corrosion begins if moisture and oxygen gain access into the concrete.¹

In good quality concrete, the carbonation process is very slow. It has been estimated that the process will proceed at a rate up to 0.04 in. (1 mm) per year. The process requires constant change in moisture levels from dry to damp to dry. Carbonation will not occur when concrete is constantly under water.



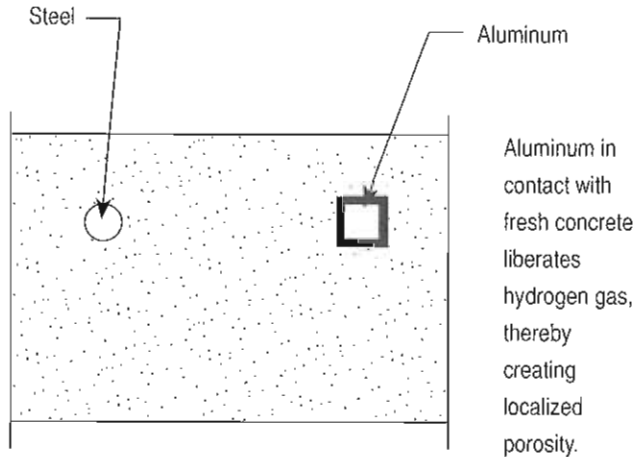
¹Vaysburd, A.M., Sabnis, G.M., and Sorokko, R., Theoretical Aspects and Testing Methods of Concrete Carbonation, Proceedings, International Conference on Life Prediction of Corrodible Structures, Hawaii, 1991, pp. 34/1-34/16.

Structural Steel Member Corrosion

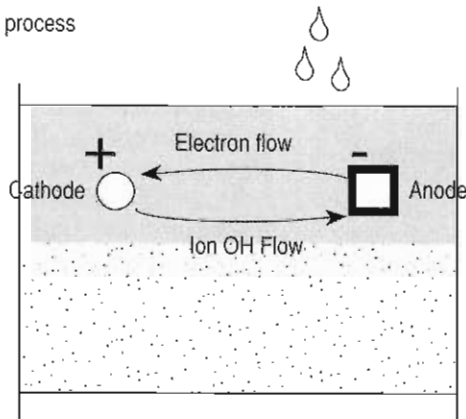


Corrosion of embedded metals includes structural members such as steel beams cast into concrete to form a composite member, or to provide fire protection. The top flange of a beam is susceptible to corrosion when a crack or construction joint intersects the flange. Moisture and corrosive salts are trapped on the flange, providing an ideal environment for corrosive activity. Corrosion on the top flange exerts a *jacking force* on the concrete above the flange. When the force is sufficient, delamination occurs. Evidence of slab separation from the beam then becomes apparent from the underside of the slab.

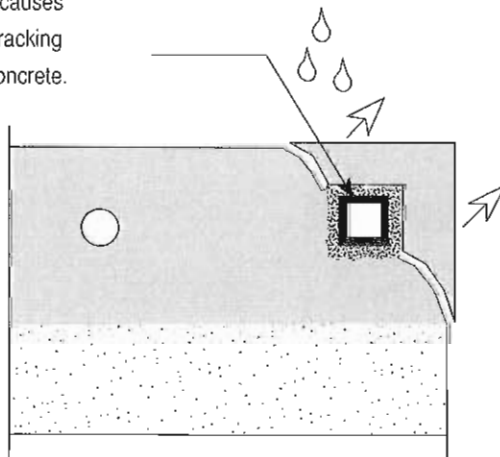
Dissimilar Metal Corrosion



Note: shaded area denotes level of moisture penetration and active electrolyte. If chlorides are present, the process is accelerated.



Corrosion occurs here. Aluminum oxide causes expansion and cracking of surrounding concrete.



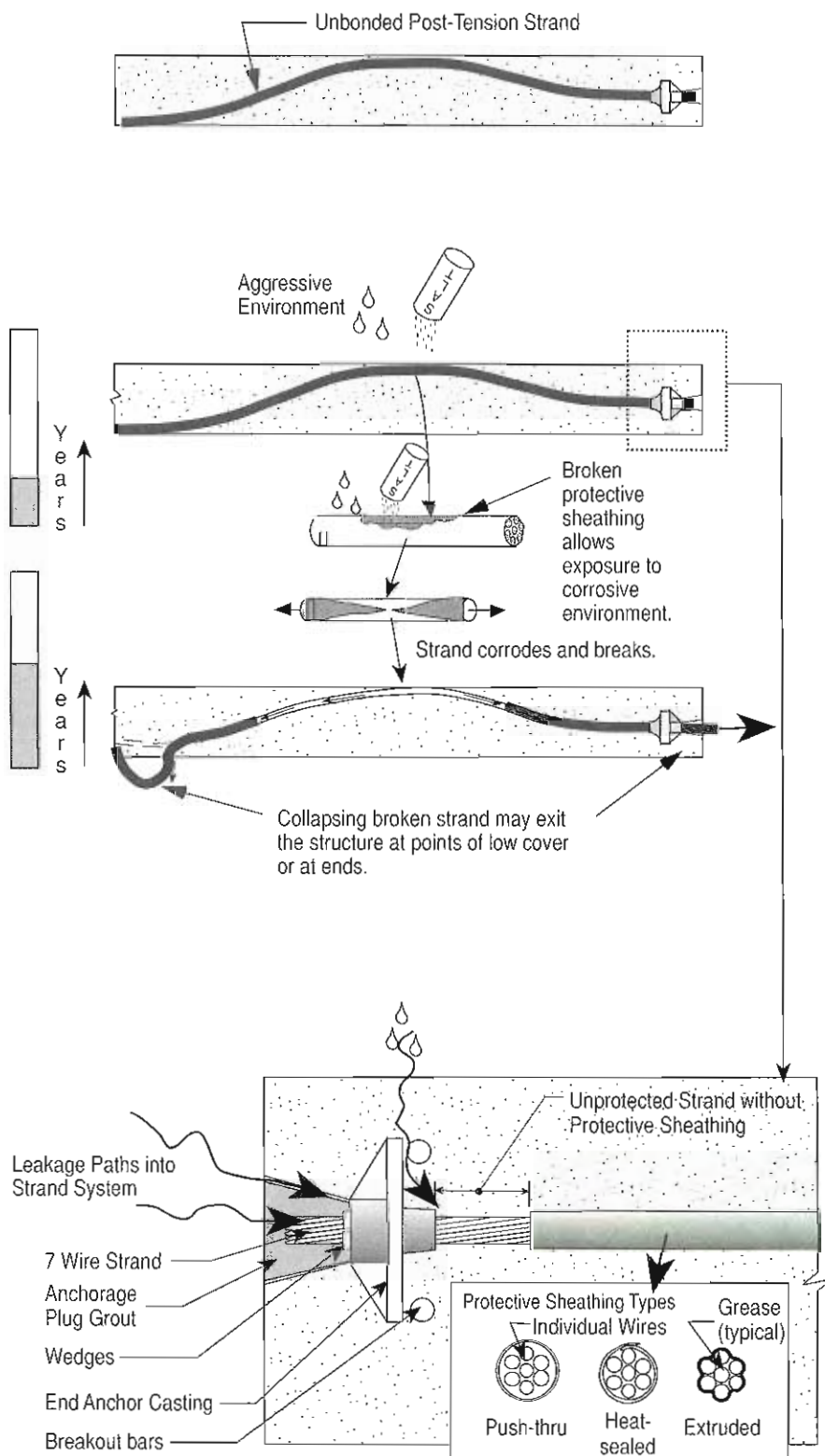
Corrosion can take place in concrete when two different metals are cast into a concrete structure, along with an adequate electrolyte. A moist concrete matrix provides for a good electrolyte. This type of corrosion is known as *galvanic*. Each metal has a unique tendency to promote *electrochemical activity*. Gold, for example, is very active, while zinc is inactive. Below is a list of metals in order of increasing activity:

1. Zinc
2. **Aluminum**
3. **Steel**
4. Iron
5. Nickel
6. Tin
7. Lead
8. Brass
9. Copper
10. Bronze
11. Stainless Steel
12. Gold

When two metals are in contact via an active electrolyte, the less active metal (lower number) in the series is corroded.

One of the most common situations found in concrete is the use of aluminum cast into reinforced concrete. Aluminum was used as an electrical conduit, and more recently, as hand rails. Aluminum has less activity than steel; therefore, the aluminum is the metal that corrodes. The steel will actually become cleaned, and the aluminum surfaces will grow a white oxide, which will cause tensile forces to crack the surrounding concrete.

Post-Tension Strand Corrosion



Corrosion of unbonded post-tension strands has become a common problem for structures exposed to aggressive environments. Buildings exposed to ocean salt spray and parking structures exposed to de-icing salts are typical locations for unbonded strand corrosion. Unbonded post-tension strands are protected from corrosion by protective grease and sheathing. Aggressive agents can penetrate the protective systems when inadequate concrete cover is subject to damage by heavy wheel loads.

Another common problem is poor corrosion protection of the end anchorages due to porous or cracked anchorage plug grout. Once corrosion promoters enter the strand system, corrosion may begin.

Corrosion of unbonded strands is a serious condition. Unlike mild reinforcement, post tension strands have stored energy from the stressing operation. It is not uncommon for strands to be stretched 8 inches (203mm) per 100 feet (30.5m). Corrosion of the strand reduces the cross section and results in an increasing stress level in the strand. Breakage occurs when the stress level exceeds the capacity of the steel. When the breakage occurs, it can be explosive, resulting in the freed strand collapsing on itself and, in some cases, exiting the structure at ends or locations where low cover exists. Locating broken strands may be difficult if the strands do not exit the structure. Longitudinal cracking may be an indication of a broken strand.

Additional Sources of Information

American Concrete Institute, SP-102, Steel Corrosion in Concrete: Causes and Restraints, Detroit, 1987.

ACI 201.2R-77, Guide to Durable Concrete.

ACI 318-83, Corrosion of Metals in Concrete.

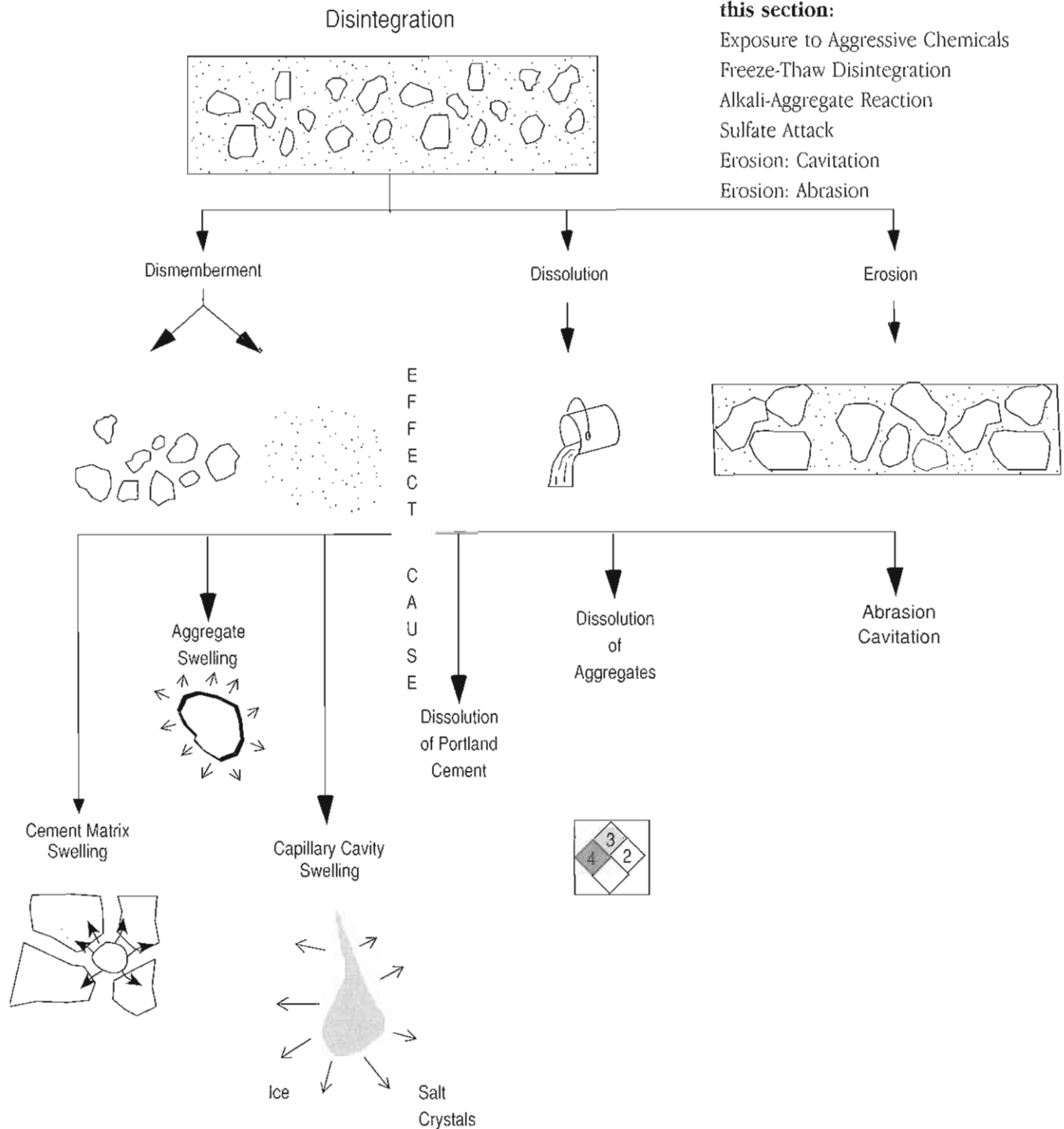
Protection of Steel in Prestressed Concrete Bridges, NCHRP Report No. 90, 1970.

Chloride Corrosion of Steel in Concrete, ASTM STP 627, American Society for Testing and Materials, Philadelphia, PA., 1977.

Section 2: Disintegration Mechanisms

The following topics are covered in this section:

Exposure to Aggressive Chemicals
Freeze-Thaw Disintegration
Alkali-Aggregate Reaction
Sulfate Attack
Erosion: Cavitation
Erosion: Abrasion



Introduction to Disintegration Mechanisms

This section includes discussions of various processes which cause the constituents of concrete to (1) dissolve, (2) be forced to come apart (dismemberment) through expansive volume change mechanisms, or (3) become worn away through abrasion or cavitation. Aggressive chemical exposures (either man-made or natural) can cause the concrete to alter its chemical makeup, resulting in changes in its mechanical properties. Depending upon the type of attack, the concrete can soften or disintegrate, in part or in whole.

Water can be one of the most aggressive environments causing disintegration. If concrete is saturated with water and is subject to freezing, the expansive force of the increase in volume (ice compared to water) may cause the concrete to come apart in small pieces. Similar to the effects of ice is the swelling of salt crystals in the concrete surface subject to salt solutions.

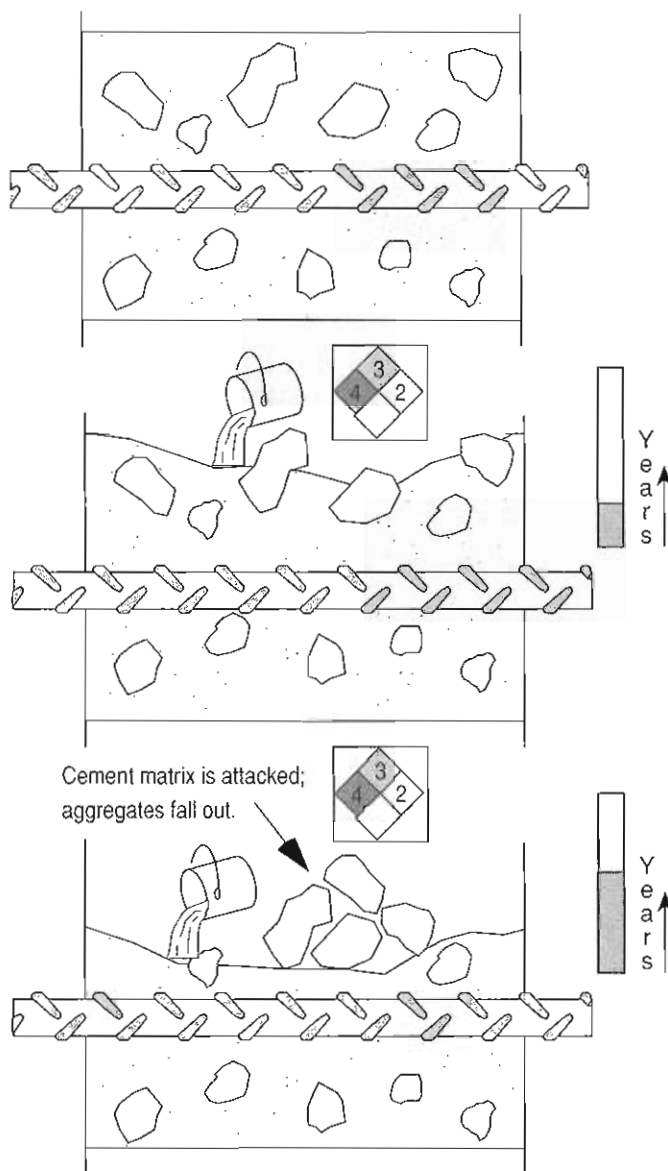
Not all disintegration mechanisms are caused by external factors. Alkali-aggregate reactions are internally contained within the originally constructed concrete. They result in swelling of the affected aggregate.

Exposure to Aggressive Chemicals

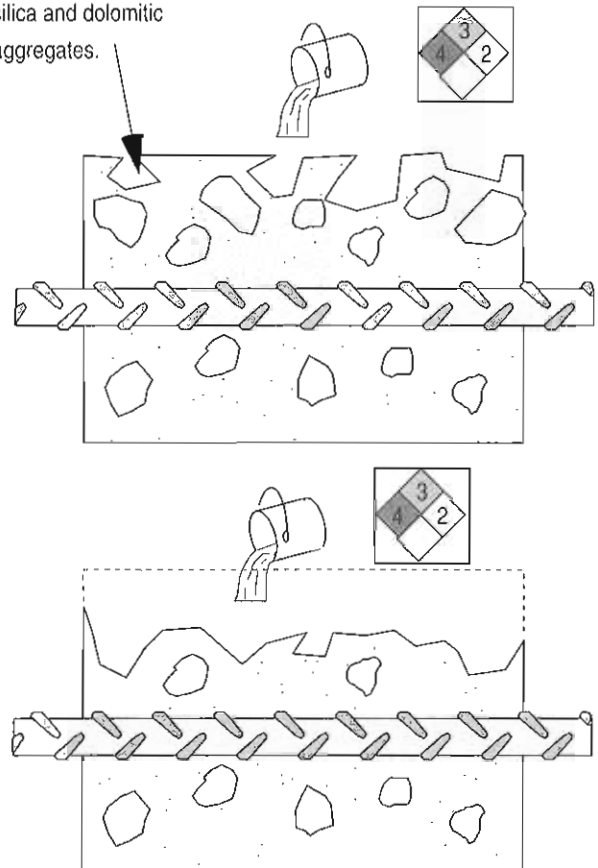
Certain chemicals in solution will attack various constituents of concrete. Aggressive chemicals can be categorized as follows:

1. Inorganic acids
2. Organic acids
3. Alkaline solutions
4. Salt solutions
5. Miscellaneous

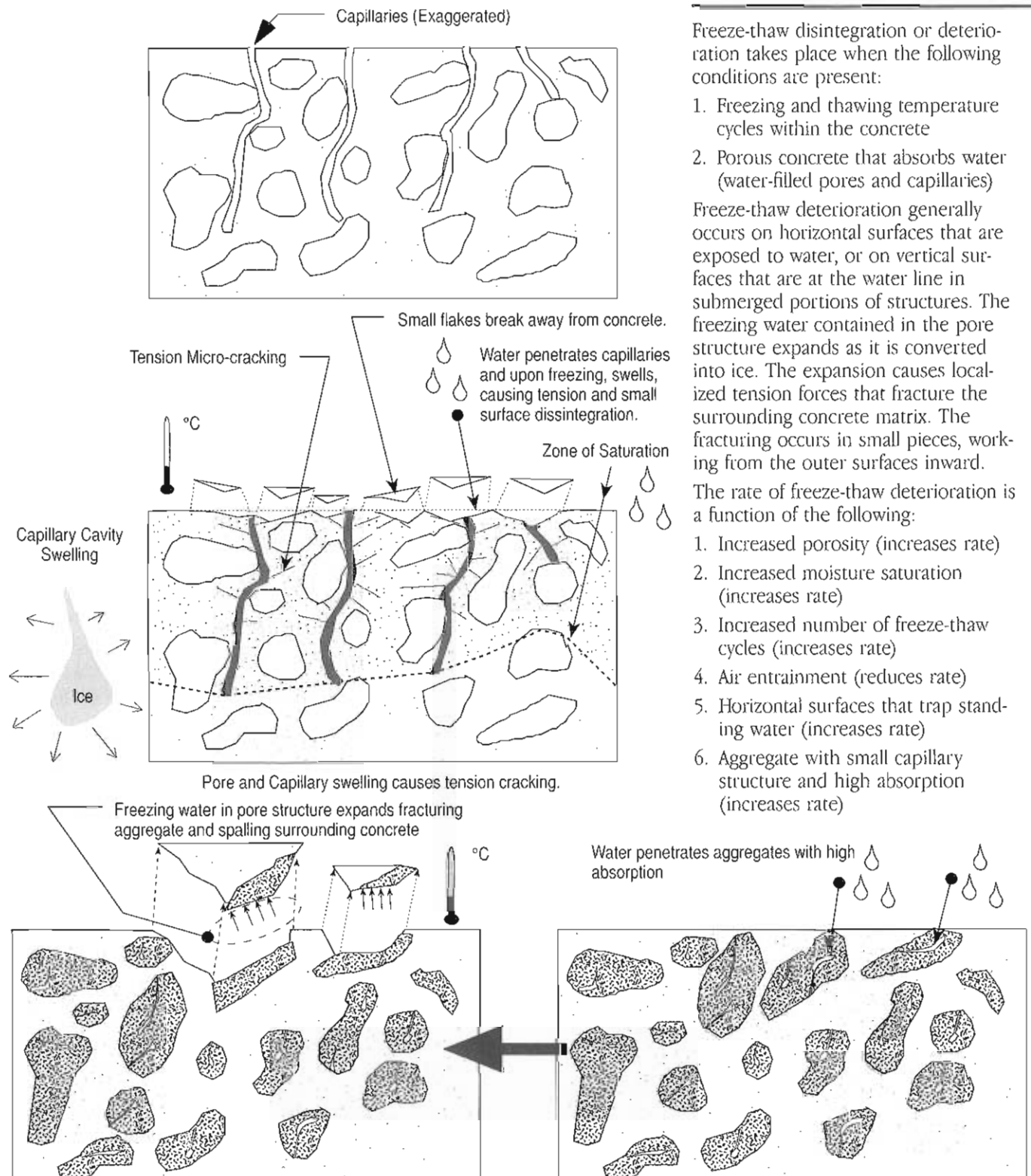
Acid attack on concrete is the reaction between the acid and the calcium hydroxide of the hydrated Portland cement. The reaction produces water soluble calcium compounds, which are leached away. When limestone or *dolomitic* aggregates are used, the acid may dissolve them.



Acids dissolve silica and dolomitic aggregates.



Freeze-Thaw Disintegration



Freeze-thaw disintegration or deterioration takes place when the following conditions are present:

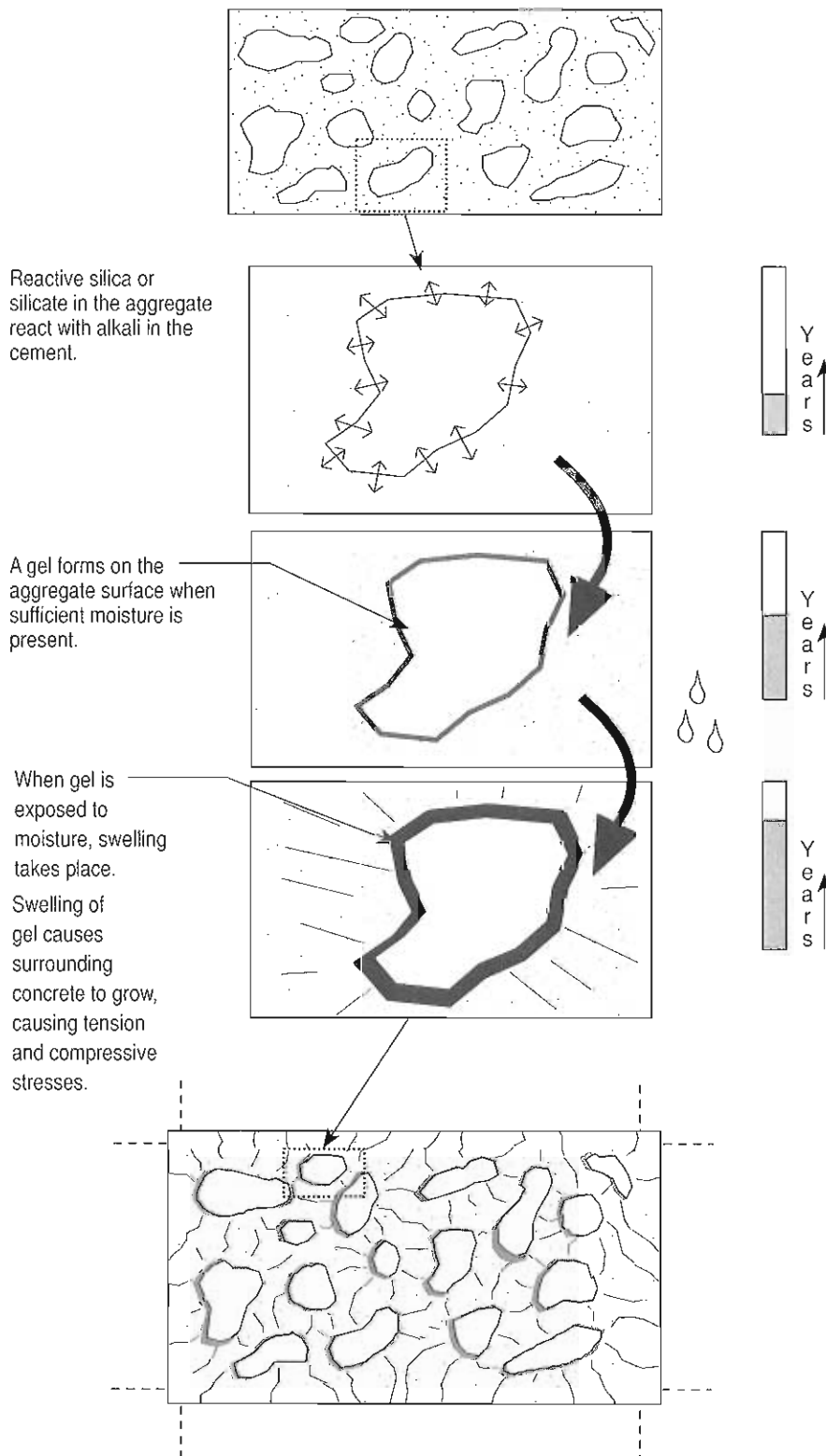
1. Freezing and thawing temperature cycles within the concrete
2. Porous concrete that absorbs water (water-filled pores and capillaries)

Freeze-thaw deterioration generally occurs on horizontal surfaces that are exposed to water, or on vertical surfaces that are at the water line in submerged portions of structures. The freezing water contained in the pore structure expands as it is converted into ice. The expansion causes localized tension forces that fracture the surrounding concrete matrix. The fracturing occurs in small pieces, working from the outer surfaces inward.

The rate of freeze-thaw deterioration is a function of the following:

1. Increased porosity (increases rate)
2. Increased moisture saturation (increases rate)
3. Increased number of freeze-thaw cycles (increases rate)
4. Air entrainment (reduces rate)
5. Horizontal surfaces that trap standing water (increases rate)
6. Aggregate with small capillary structure and high absorption (increases rate)

Alkali-Aggregate Reactions



Alkali-aggregate reactions (AAR) may create expansion and severe cracking of concrete structures and pavements. The mechanisms that cause alkali-aggregate reactions are not fully understood. What is known about this type of reaction is that certain aggregates, such as reactive forms of silica, react with potassium, sodium, and calcium hydroxide from the cement and form a gel around the reacting aggregates.

When the gel around the aggregate is exposed to moisture, it expands, creating forces that cause tension cracks to form around the aggregate. [Moisture content of the concrete must be approximately 80 percent: relative humidity at 70°F–75°F (21°C–24°C).]

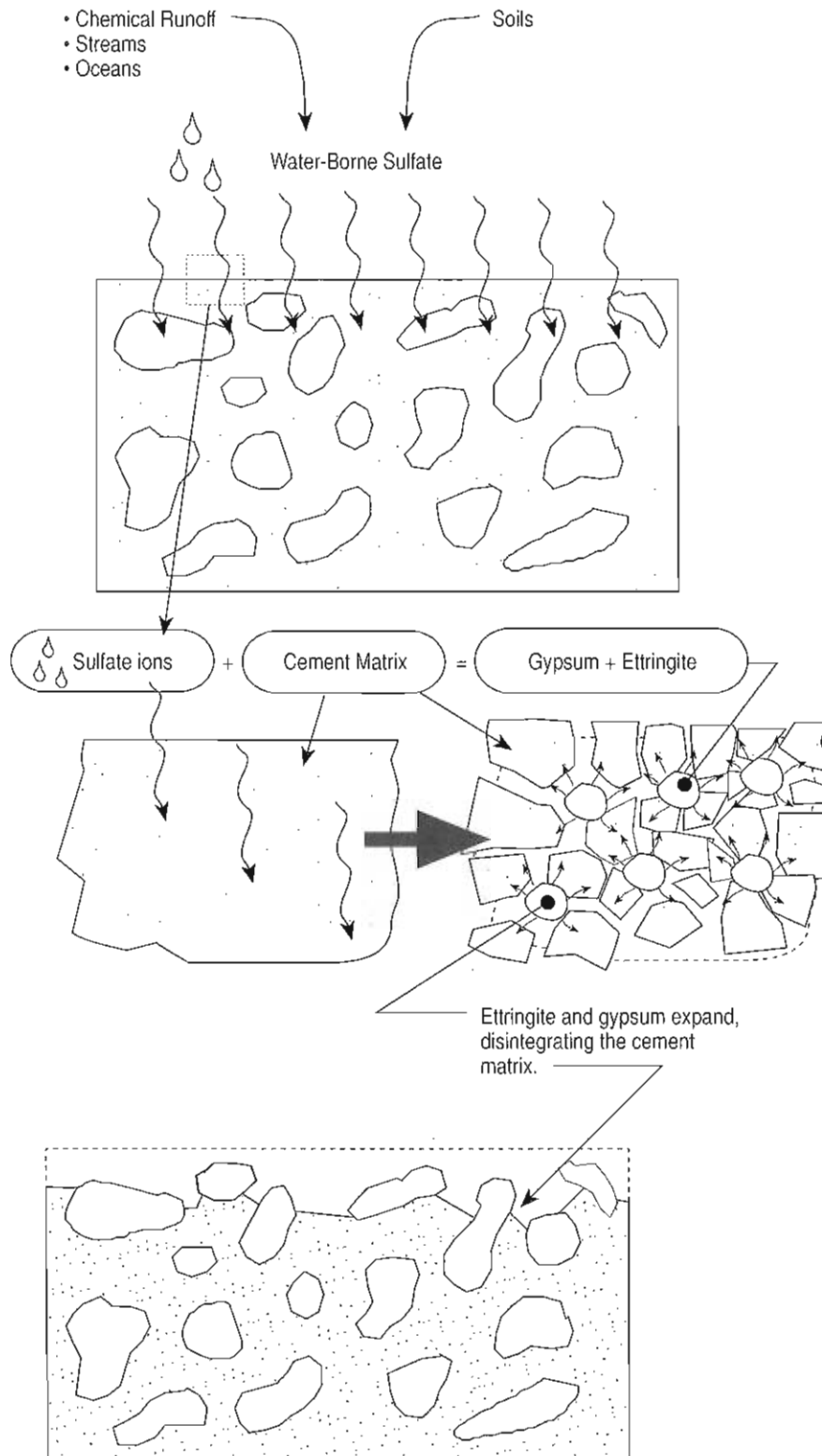
Unconfined concrete undergoing AAR exhibits tell-tale signs of surface map cracking on exposed surfaces. Once the cracking has formed, more moisture penetrates the concrete, accelerating the alkali-aggregate reaction and allowing additional freeze-thaw damage.

The alkali-aggregate reaction may go unrecognized for some period of time, possibly years, before associated severe distress will develop.

Usually, testing for the presence of alkali-aggregate reaction is conducted by petrographic examination of concrete. Recently, a new method capable of monitoring possible reaction has been developed. This method utilizes the uranyl (uranium) acetate fluorescence technique and is rapid and economical.¹

¹Handbook for the Identification of Alkali-Silica Reactivity in Highway Structures, SHRP-C/FR-91-101, National Research Council, Washington, D.C., 1991.

Sulfate Attack



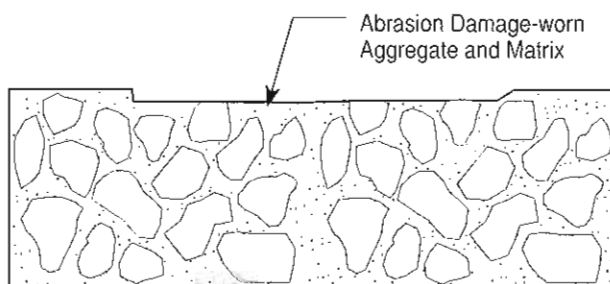
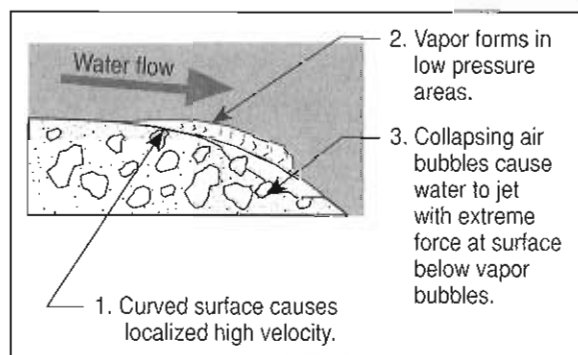
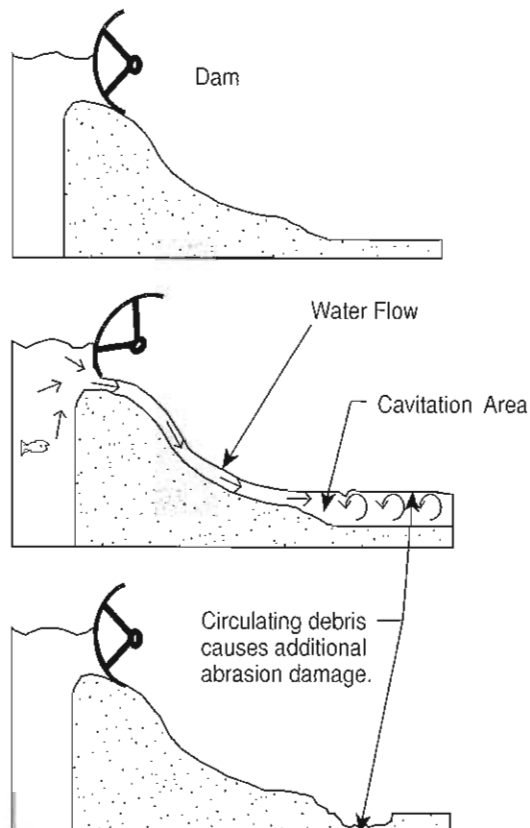
The presence of soluble sulfates (principally those of sodium, calcium and magnesium) is common in areas of mining operations, chemical and paper milling industries. Sodium and calcium are the most common sulfates in soils, water and industrial processes. Magnesium sulfates are less common, but more destructive. Soils or waters containing these sulfates are often called "alkali" soils or waters.

All sulfates are potentially harmful to concrete. They react chemically with cement paste's hydrated lime and hydrated calcium aluminate. As a result of this reaction, solid products with volume greater than the products entering the reaction are formed.

The formation of gypsum and ettringite expands, pressurizes and disrupts the paste. As a result, surface scaling and disintegration set in, followed by mass deterioration.

Sulfate resistance of the concrete is improved by a reduction in water-cement ratio and an adequate cement factor, with a low tricalcium aluminate and with proper air entrainment. With proper proportioning, silica fume (microsilica), fly ash and ground slag generally improve the resistance of concrete to sulfate attack, primarily by reducing the amount of reactive elements (such as calcium) needed for expansive sulfate reactions.

Erosion



Cavitation

Cavitation causes erosion of concrete surfaces resulting from the collapse of *vapor bubbles* formed by pressure changes within a high velocity water flow. When vapor bubbles form, they flow downstream with the water. When they enter a region of higher pressure, they collapse (implode) with great impact. The formation of vapor bubbles and their subsequent collapse is called cavitation. The energy released upon their collapse causes "cavitation damage." Cavities are formed near curves and offsets, or at the center of vortices. Cavitation damage results in the erosion of the cement matrix, leaving harder aggregate in place. At higher velocities, the forces of cavitation may be great enough to wear away large quantities of concrete.

Cavitation damage is avoided by producing smooth surfaces and avoiding protruding obstructions to flow.

Abrasion

Abrasion is the wearing away of the surface by rubbing and friction. Generally, the surface is uniformly worn away, including the cement matrix and aggregates. Factors affecting abrasion resistance include:

1. Compressive strength
2. Aggregate properties
3. Finishing methods
4. Use of toppings
5. Curing

Additional Sources of Information

Performance of Concrete, University of Toronto Press, Toronto, Canada, 1968.

Woods, H., Durability of Concrete Construction, American Concrete Institute and Iowa State University Press, 1968.

Arni, H.T., Resistance to Weathering, ASTM STP 169A, American Society for Testing and Materials, Philadelphia, PA.

Gordon, W.A., Freezing and Thawing of Concrete—Mechanisms and Control, Monograph 3, American Concrete Institute, Detroit, 1966.

Handbook for Identification on Alkali-Silica Reactivity in Highway Structures, SHRP-C/FR-91-101, Washington, D.C., 1991.

ACI 210R-87, Erosion of Concrete in Hydraulic Structures, Manual of Concrete Practice, Part 1, 1991.

Section 3: Moisture Effects

The following topics are covered in this section:

Drying Shrinkage

Moisture Vapor Transmission

Volume Change—Moisture Content

Curling

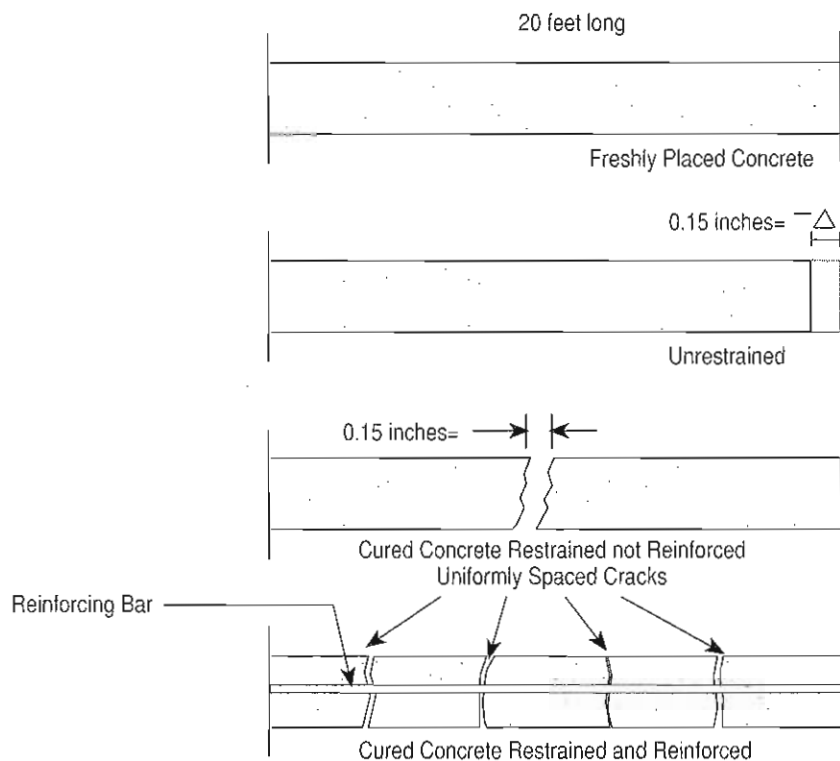
Introduction to Moisture Effects

Concrete is like fresh-cut trees made into lumber. The lumber is wet when cut, but immediately begins to dry to a moisture level equal to the surrounding environment. As the wood dries, it also reduces in volume and, in some cases, splits under the stress of shrinkage. Even seasoned wood changes volume as the moisture level in the wood changes with seasonal variations in humidity. Wood doors are easily opened in the winter when humidity is low, but swell and may be difficult to close during the humid summer months.

Concrete behaves in a similar fashion. In fresh concrete, the space between the particles is completely filled with water. The excess water evaporates after the concrete hardens. The loss of moisture causes the volume of the paste to contract. This, in turn, leads to shrinkage stress and shrinkage cracking. Like wood, concrete also changes volume in response to ambient humidity changes.

Previous sections deal with the role of moisture in freeze-thaw disintegration and the corrosion process. This section deals with the role of moisture in volume change effects and the effect of vapor transmission through concrete.

Drying Shrinkage



On exposure to the atmosphere, concrete loses some of its original water through evaporation and shrinks. Normal weight concrete shrinks from 400 to 800 microstrains (one microstrain is equal to 1×10^{-6} in./in. (mm/mm)).

Example of Drying Shrinkage

slab length = 20 feet (6m)
 drying shrinkage = 600 microstrains
shrinkage of slab = 0.15 inches (4mm)

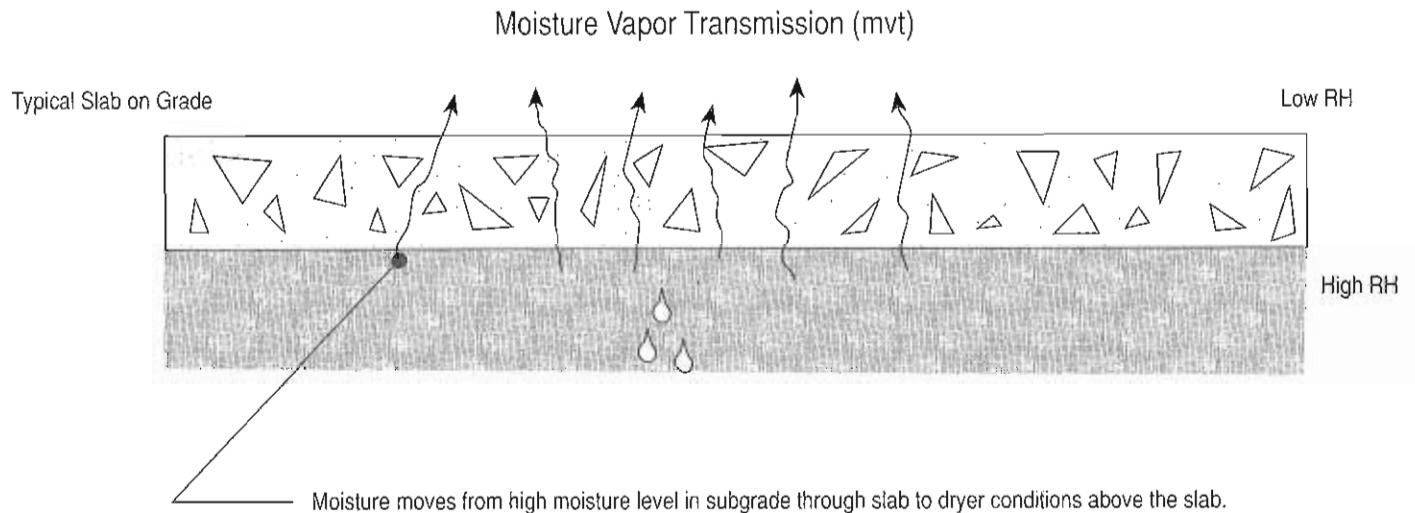
Drying shrinkage, if unrestrained, results in shortening of the member without a build-up of shrinkage stress. If the member is restrained from moving, stress build-up may exceed the tensile strength of the concrete. This over-stressing results in dry shrinkage cracking. Correct placement of reinforcing steel in the member distributes the shrinkage stresses and controls crack widths.

Factors affecting drying shrinkage

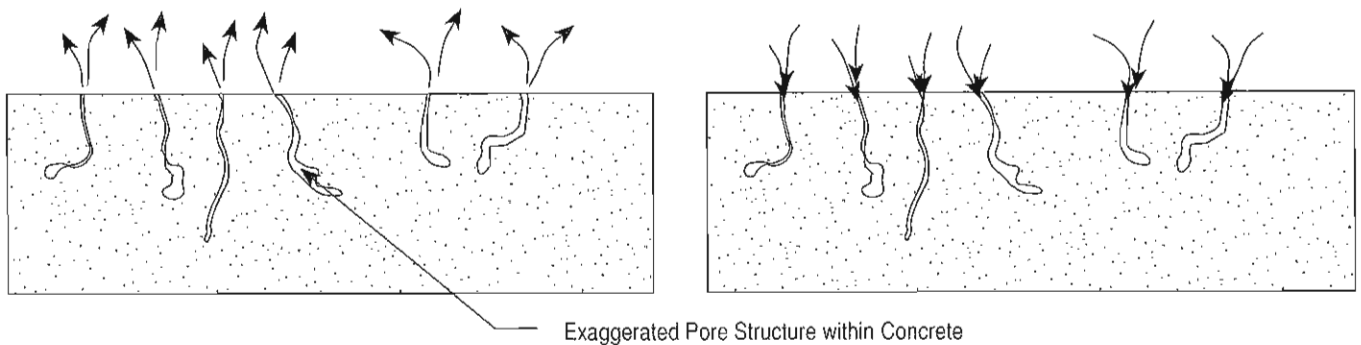
Factor	Reduced Shrinkage	Increased Shrinkage
Cement type	type I, II	type III
Aggregate size	1½" (38 mm)	¾" (19 mm)
Aggregate type	quartz	sandstone
Cement content	550 lb/cy (325 kg/m³)	700 lb (415 kg/m³)
Slump	3" (76 mm)	6" (152 mm)
Curing	7 days	3 days
Placement temperature	60°F (16°C)	85°F (29°C)
Aggregate state	washed	dirty

Moisture Vapor Transmission

Water vapor travels through concrete when a structural member's surfaces are subject to different levels of relative humidity (RH). Moisture vapor travels from high RH to low RH. The amount of moisture vapor transmission is a function of the RH gradient between faces, and the permeability of the concrete.



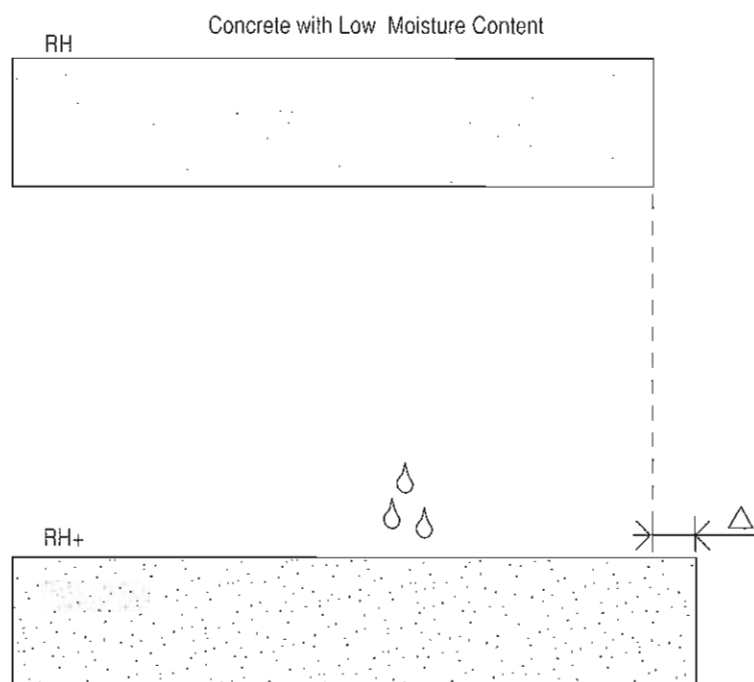
Moisture vapor also moves into and out of the pore structure of concrete as differences occur in relative humidity. Moisture vapor moves from high humidity to low humidity. Vapor also moves with changes in temperature. When the temperature rises, vapor expands and moves out of the pore structure.



Volume Change—Moisture Content

Concrete changes length depending upon its *moisture content*. Moist concrete that dries out will shrink, while dry concrete that becomes moist will expand. Concrete may follow seasonal changes: hot, humid summers generate higher moisture contents, while cold, dry winters reduce moisture contents.

Establishing values for the amount of shrinkage or expansion caused by a change in moisture content can be carried out by estimating, based on dry shrinkage values. Drying shrinkage values are based on an initial 100 percent moisture content reduced to an ambient relative humidity of about 50 percent.

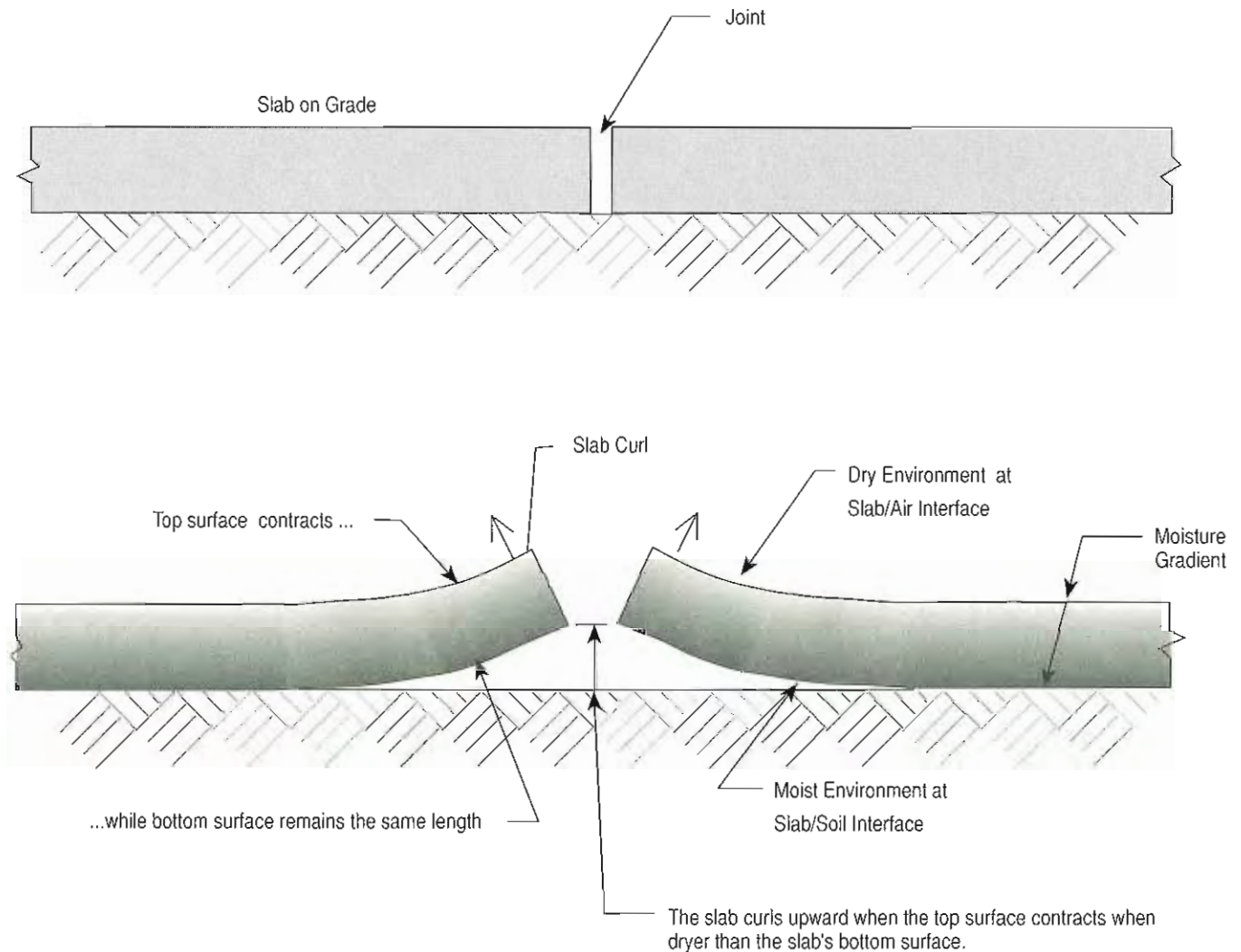


Concrete with High Moisture Content grows in volume relative to concrete with low moisture content.

Curling

Curling is a common problem with slabs cast on grade. Curling is caused by uneven moisture and temperature gradients across the thickness of the slab. Curling is increased as drying shrinkage progresses. Slab surfaces are usually dry on top, where they are exposed to air, and moist on the bottom, where they are exposed to soil. The drier surface has a tendency to contract in length relative to the moist bottom surface. The contraction of the top surface can only be relieved by the slab curling upward.

Temperature gradients across a slab can create the same problems as moisture gradients. The typical situation is solar heating of the slab's top surface, causing a higher temperature on this surface. The top surface then has a tendency to grow in length relative to the bottom surface. Stress relief occurs when the slab curls downward.



Additional Sources of Information

ACI 209R-82, Prediction of Creep, Shrinkage and Temperature Effects in Concrete Structures.

Mindess, S., Young, J.F., Concrete, Prentice Hall, Inc., 1981, pp. 481–519.

Emmons, P.H., Selecting Concrete Repair Materials for Long-Term Durability, Proceedings of the 2nd National Concrete Engineering Conference, Chicago, 1992.

Section 4: Thermal Effects

The following topics are covered in this section:

Thermal Volume Change

Uneven Thermal Loads

Uneven Thermal Loads:

Continuous Spans

Restraint to Volume Change

Early Thermal Cracking of Freshly Placed Concrete

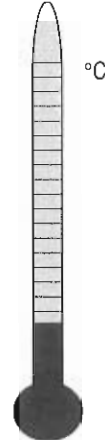
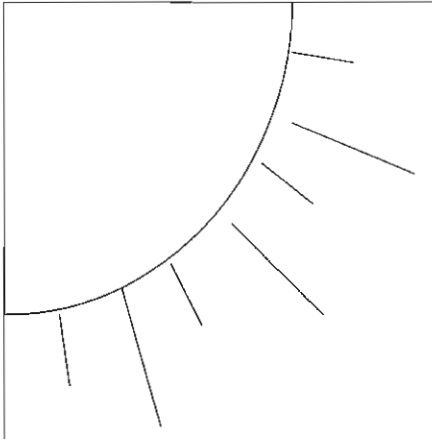
Thermal Movements in Existing Cracks

Uneven Thermal Loads: Cooling

Tower Shell

Fire Damage

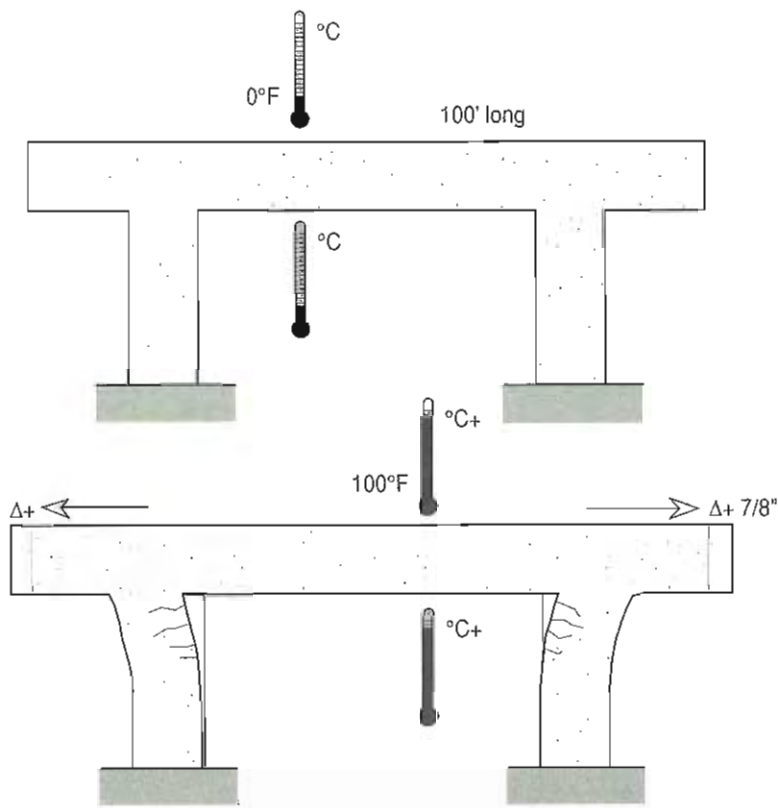
Introduction to Thermal Effects



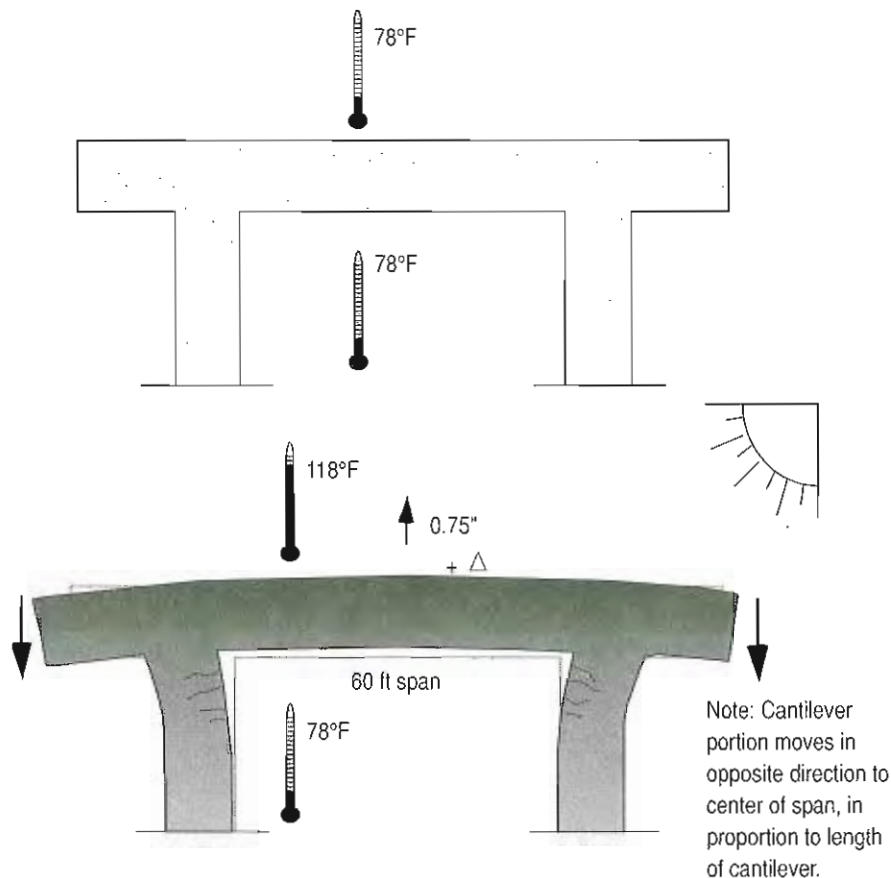
The effect of temperature on concrete structures and members is one of volume change. The volume relationship to temperature is expressed by the coefficient of thermal expansion/contraction. Volume changes create stress when the concrete is restrained. The resulting stresses can be of any type: tension, compression, shear, etc. The stressed conditions may result in undesirable behavior such as cracking, spalling and excessive deflection.

Thermal Volume Change

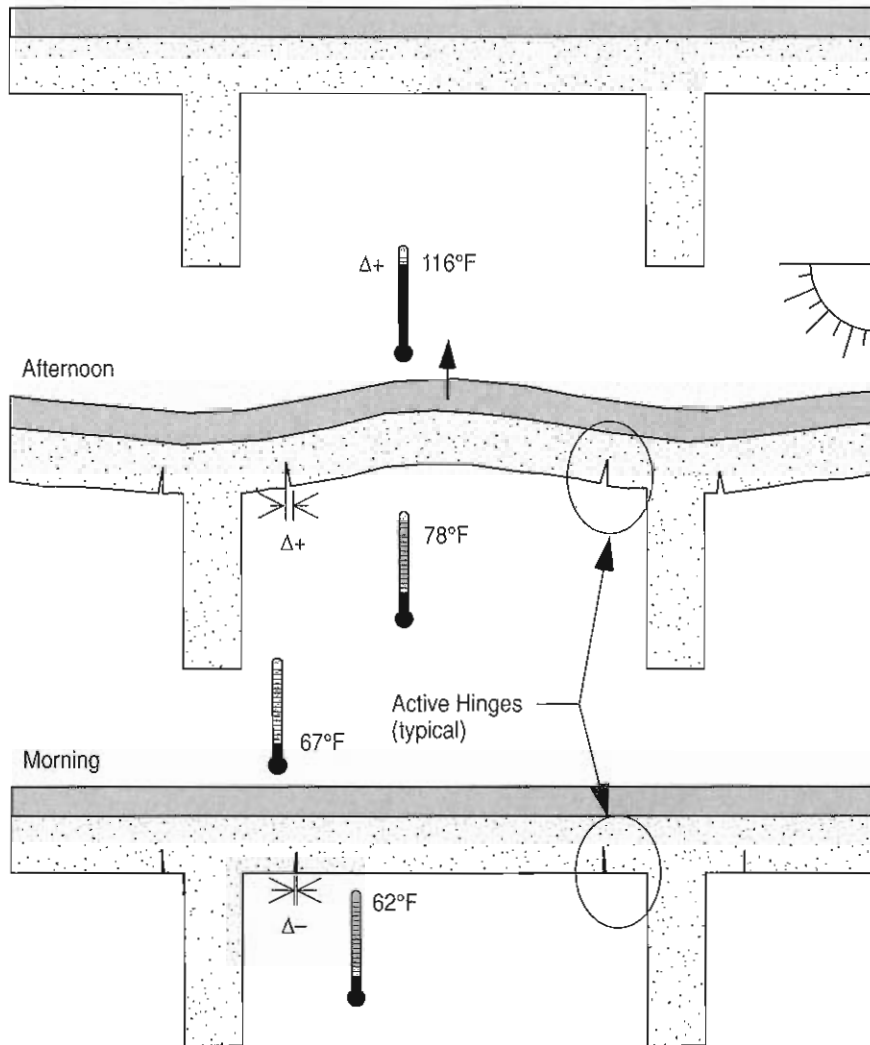
Concrete, like all materials, changes volume when subjected to temperature changes. An increase in temperature increases the volume of concrete; conversely, a decrease in temperature reduces the volume of concrete. The thermal coefficient of concrete is approximately 5×10^{-6} in/in/°F (9×10^{-6} mm/mm/°C). A change of 100°F (38°C) in a 100' (30.5m) length will change the overall length by 7/8" (22mm).



Uneven Thermal Loads



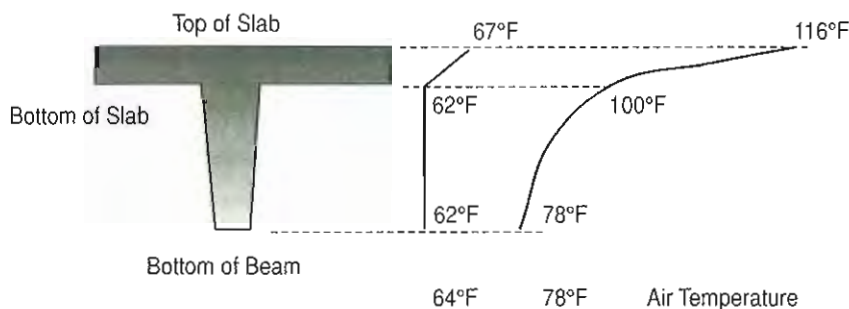
Temperature gradients exist in many structures. The temperature on the surface of a deck slab exposed to direct sunlight may reach 118°F (48°C), while the underside of the deck may be only 78°F (26°C)—a 40°F (22°C) difference known as *diurnal solar heating*. This causes the top surface to have a tendency to expand more than the bottom surface. This results in an upward movement during heating, and a downward movement during cooling. A precast double-T shaped structured member with a 60' (18m) span can move $\frac{3}{4}$ " (19mm) upward at midspan from normal diurnal solar heating, causing the ends to rotate and stress the ledger beam bearing pads and concrete.



Continuous Spans

Diurnal solar heating affects structures differently depending upon their configuration. Simple span structures deflect up and down and are free to rotate at end supports. Continuous structures may behave differently because they are not free to rotate at supports. If enough thermal gradient exists, together with insufficient tensile capacity in the bottom of the member, a hinge may form. Hinges may occur randomly in newly formed cracks, or may form in construction joints near the columns. Hinges open and close with daily temperature changes.

Working Example of Temperature Gradients



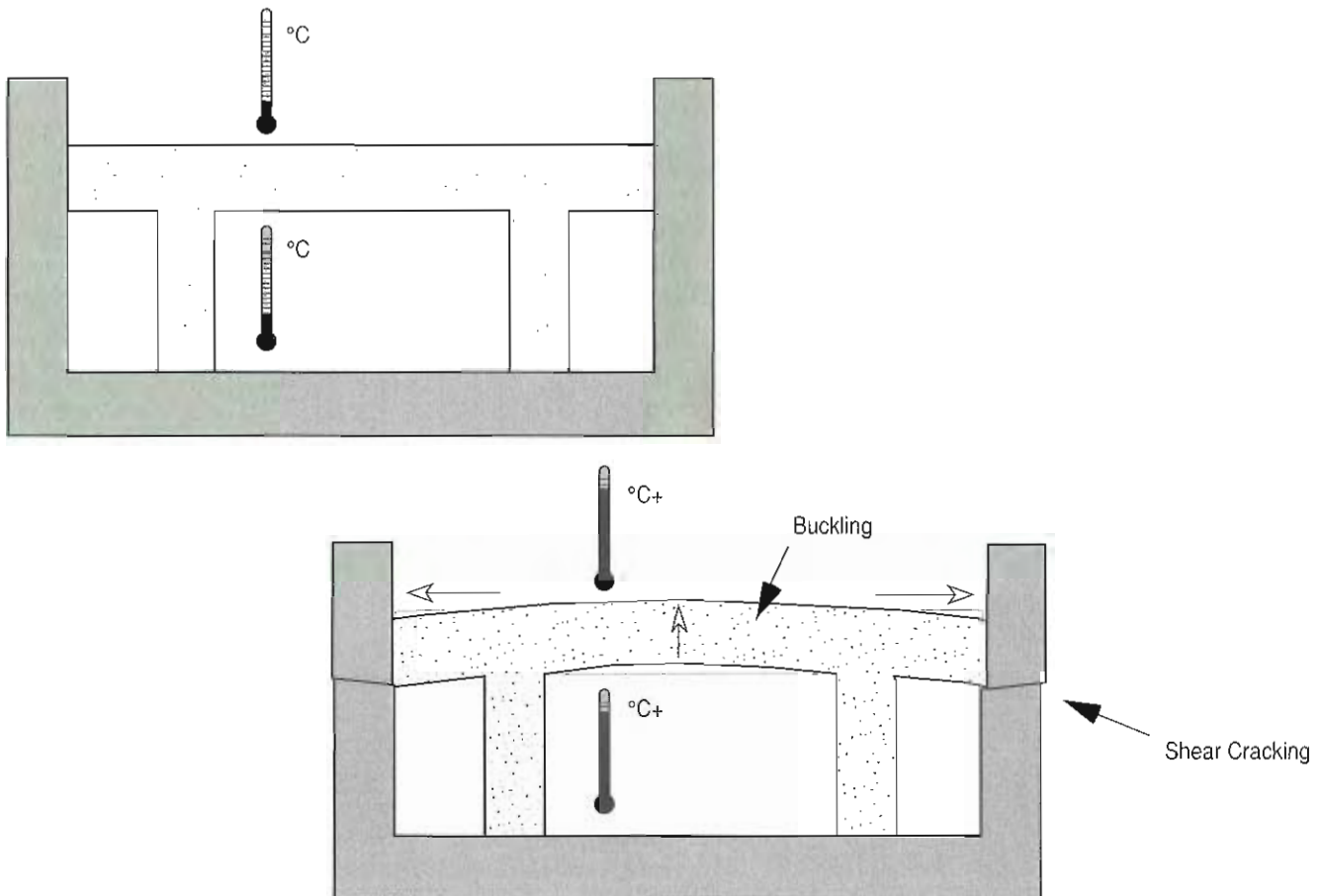
Restraint to Volume Changes

If a structural member is free to deform as a result of changes in temperature, moisture, or loads, there is no build-up of internal stress. If the structural member is restrained, stress build-up occurs and can be very signifi-

cant. When stress build-up is relieved, it will occur in the weakest portion of the structural member or its connection to other parts of the structure. The stress may result in *tension cracks*, *shear cracks*, and *buckling*.

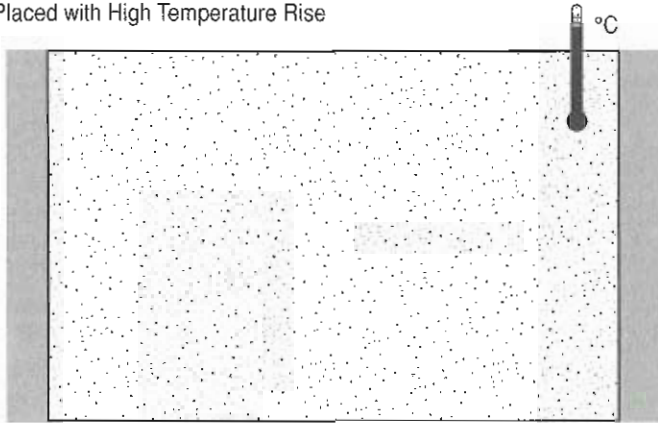
Working Example

Elastic modulus of concrete	= 4,000,000 psi (2.8×10^4 MPa)
Length of concrete member	= 100 feet (30.5m)
Temperature change	= 100°F (38°C)
Thermal coefficient	= 5×10^{-6} in/in/°F (9×10^{-6} mm/mm/°C)
Unit strain	= $(100^\circ\text{F}) \times (5 \times 10^{-6} \text{ in/in/}^\circ\text{F}) = 500 \times 10^{-6} \text{ in/in}$ ($342 \times 10^{-6} \text{ mm/mm}$)
Unit stress (if restrained)	= 2,000 psi (14 MPa) = elastic modulus \times unit strain
Force per square foot	= 288,000 psf = 2,000 psi \times 144 in ² /ft ²

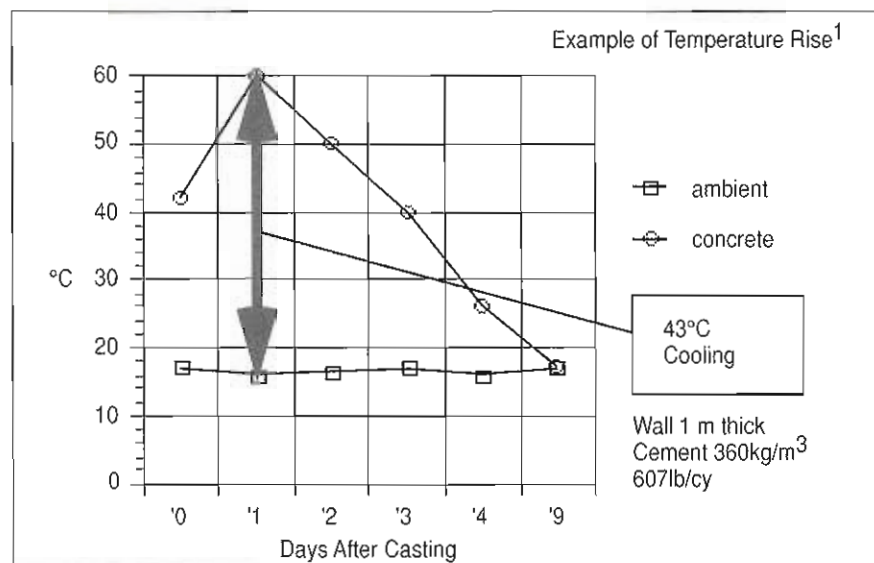
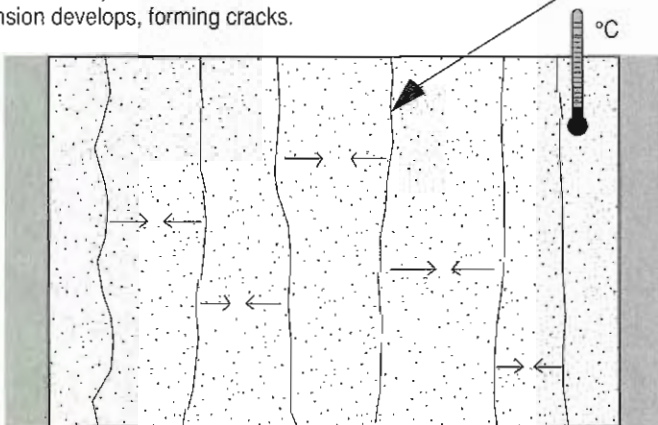


Early Thermal Cracking of Freshly Placed Concrete

Concrete Placed with High Temperature Rise



When concrete cools, the member contracts. If restraint occurs, tension develops, forming cracks.



Freshly placed concrete undergoes a temperature rise from the heat generated by the cement *hydration*. The heat rise occurs over the first few hours or days after casting, then cools to the surrounding ambient temperature. When cooling takes place two or three days after casting, the concrete has very little tensile strength. Weak tensile strength, coupled with a thermally contracting member, provide for the likelihood of tension cracks.

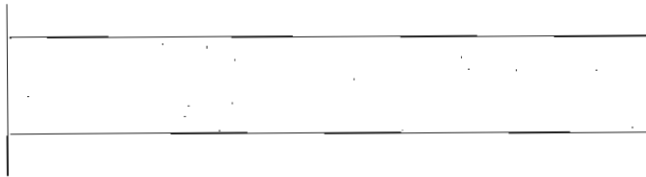
Factors affecting early temperature rise include:

1. **Initial temperature of materials.** Warm materials lead to warm concrete. Aggregate temperature is the most critical.
2. **Ambient temperature.** Higher ambient temperatures lead to higher peaks.
3. **Dimensions.** Larger sections generate more heat.
4. **Curing.** *Water curing* dissipates the build-up of heat. *Thermal shocking* should be avoided.
5. **Formwork removal time.** Early removal of formwork reduces peak temperature.
6. **Type of formwork.** Wood forms produce higher temperatures than steel forms.
7. **Cement content.** More cement in the mix means more heat.
8. **Cement type.** Type III cement produces more heat than most other cements used.
9. **Cement replacements.** *Fly ash* reduces the amount of heat build-up.

¹Turton, C.A., "To Crack or Not to Crack?", Vol. 8, No. 11, Nov. 1974, pp 32-36.

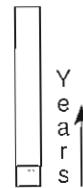
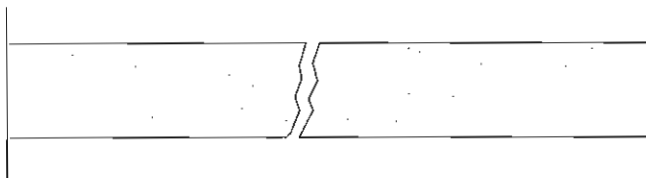
Thermal Movements in Existing Cracks

Newly Cast Concrete, Restrained

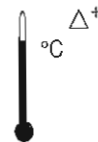
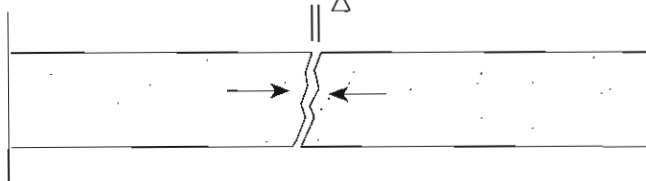


Thermal stresses can be relieved in ways other than by the formation of cracks. Cracks that were formed via other mechanisms, such as dry shrinkage cracking, may provide a location in the member where thermal change strain can be absorbed. The crack moves with the same cycle as the temperature cycle in the concrete member. Thermal movement taken up by these cracks reduces the movement at planned expansion joints.

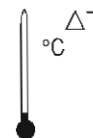
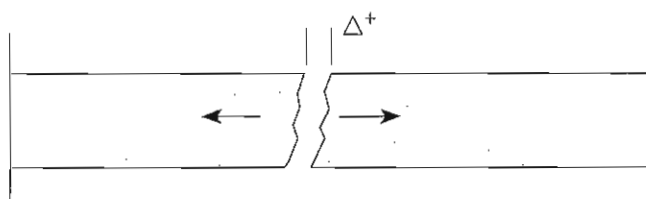
Crack is formed due to restrained dry shrinkage.



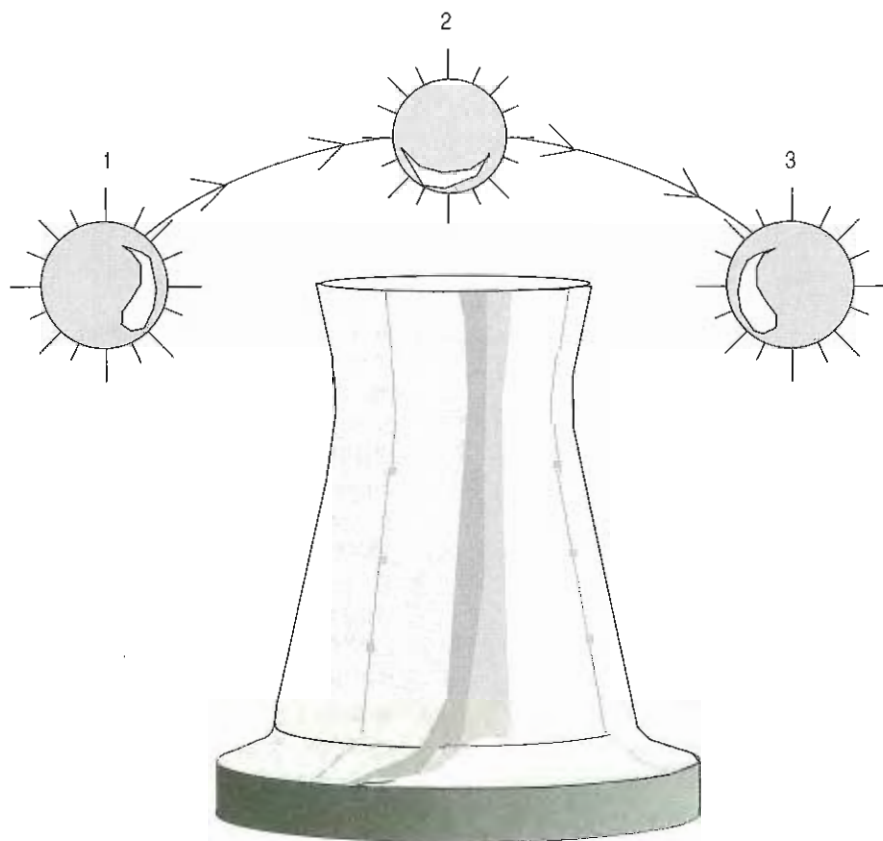
Thermal changes acting on the structure finds the crack; a rise in temperature closes the crack.



As temperatures fall, the crack opens as the concrete contracts.



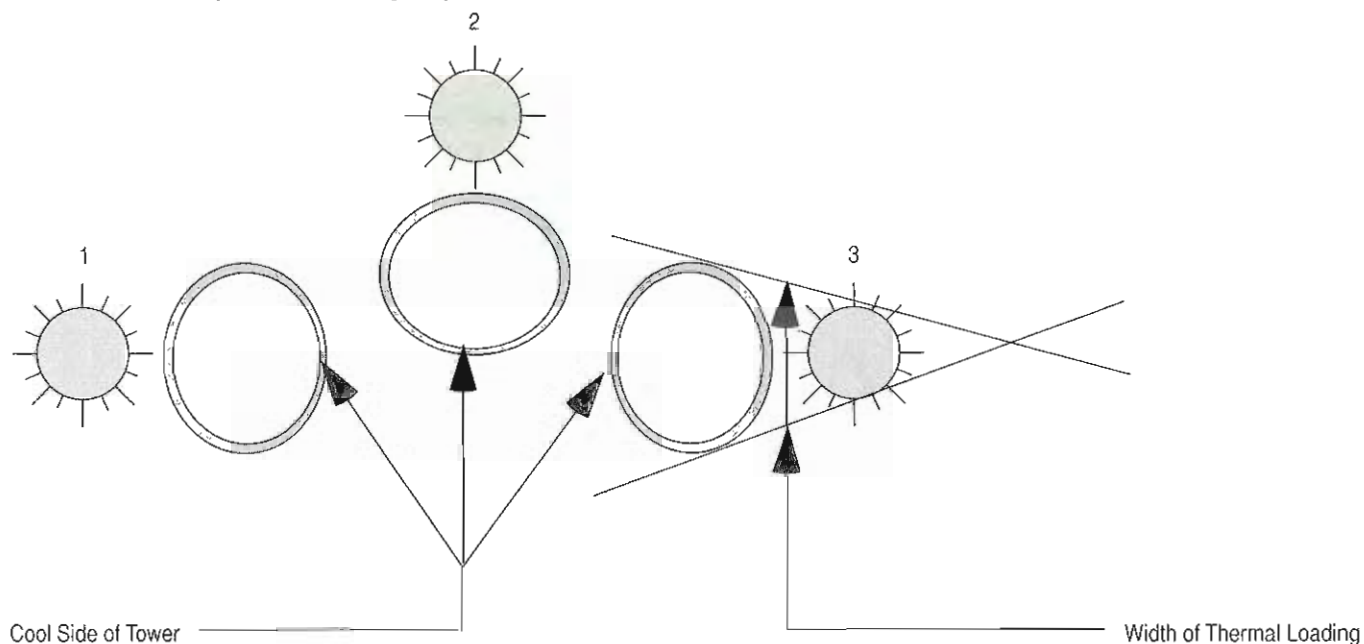
Uneven Thermal Loads



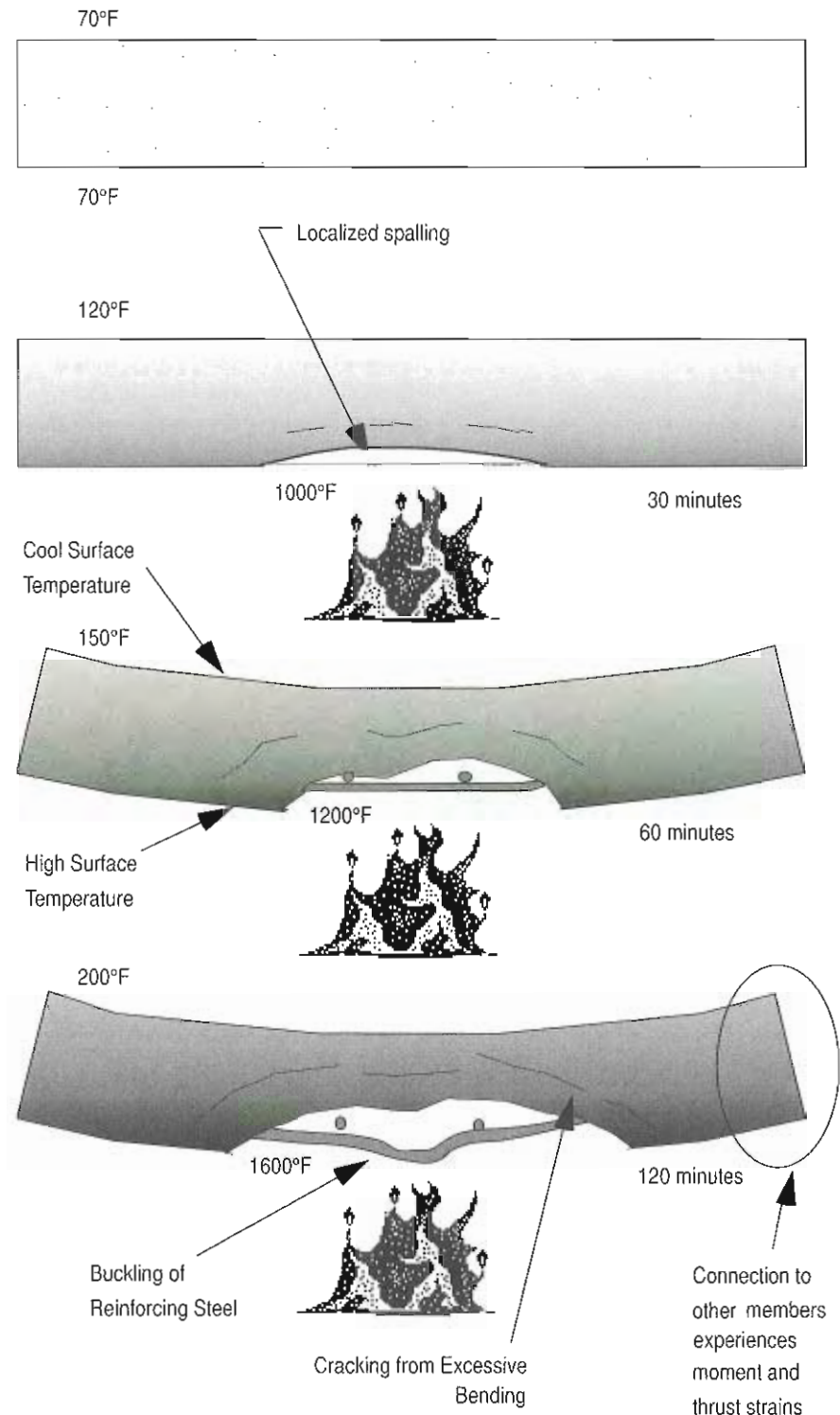
Cooling Tower Shell

Large exposed cooling towers can undergo uneven thermal stresses as the sun makes its way from east to west. The cooling tower has a relatively thin concrete shell, which is easily heated by the sun. The sun's rays hit only about 50 percent of the tower's shell at any one time. The portion of the tower that is being heated expands in size relative to the cool side of the tower. An egg-shaped cross section is formed, which moves as the sun moves, heating other portions of the tower. Problems may occur in portions of the tower where rigid framing is connected to the constantly moving outer shell.

Cooling Tower Undergoing Dynamic Thermal Loading



Fire Damage



Fire affects concrete in extreme ways, some of which are listed below:

1. Uneven volume changes in affected members, resulting in distortion, buckling, and cracking. The temperature gradients are extreme: from ambient 70°F (21°C), to higher than 1500°F (800°C) at the source of the fire and near the surface.
2. Spalling of rapidly expanding concrete surfaces from extreme heat near the source of the fire. Some aggregates expand in bursts, spalling the adjacent matrix. Moisture rapidly changes to steam, causing localized bursting of small pieces of concrete.
3. The cement mortar converts to quicklime at temperatures of 750°F (400°C), thereby causing disintegration of the concrete.
4. Reinforcing steel loses tensile capacity as the temperature rises.
5. Once the reinforcing steel is exposed by the spalling action, the steel expands more rapidly than the surrounding concrete, causing buckling and loss of bond to adjacent concrete where the reinforcement is fully encased.

Example used from ACI Fire Endurance Tests 216R Fig 7.1.1(b) Silica Aggregate 7" thick slab

Additional Sources of Information

ASTM STP 169-A, Concrete and Concrete Making Materials, American Society for Testing and Materials.

Behavior of Concrete Under Temperature Extremes, SP-39, American Concrete Institute, Detroit, 1973.

Neville, A.M., Hardened Concrete: Physical and Mechanical Aspects, Monograph 6, American Concrete Institute, Detroit, 1971.

Section 5: Load Effects

The following topics are covered in this section:

Reinforced Concrete: Basic Engineering Principles

Cracking Modes: Continuous Span
Slab/Beam-to-Column Shear

Cantilevered Members

Continuous Structures

Columns

Post-Tensioned Members

Cylindrical Structures: Buried Pipe

Cylindrical Structures: Tanks

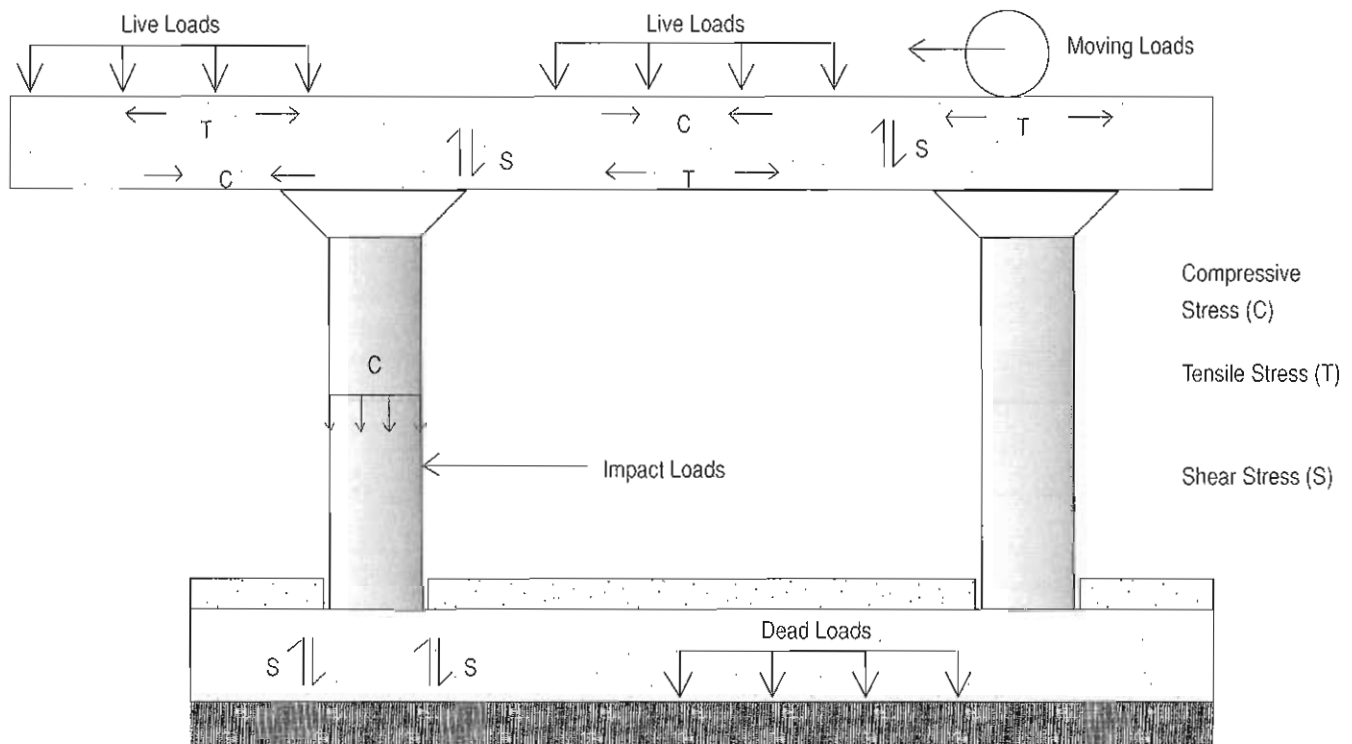
Connections: Contact Loading

Introduction to Load Effects

Concrete structures and individual members all carry loads. Some carry only the weight of the materials they are made of, while others carry loads applied to the structure. All materials change volume when subject to stress. Concrete is no exception. When subject to tensile stress, concrete stretches; when subject to compressive stress, it shortens. Reinforced concrete is a composite of two materials: plain concrete and reinforcing steel. Concrete possesses high compressive strength but little tensile strength, and reinforcing steel provides the needed strength in tension. Steel and concrete work effectively together in a composite material for several reasons:

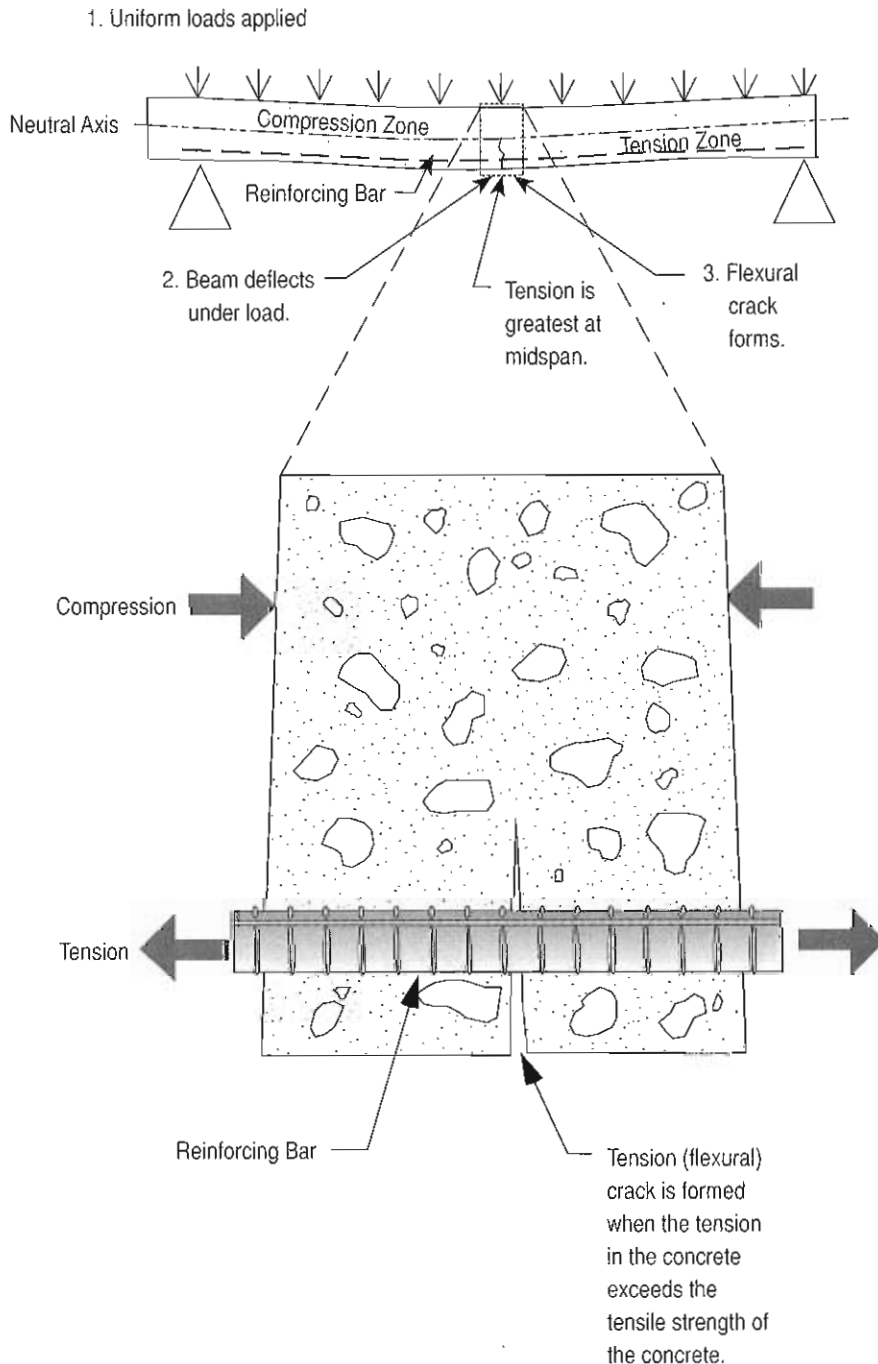
1. Similar coefficients of thermal expansion.
2. Bond between rebars and concrete prevents the slip of rebars relative to the concrete.
3. Good quality concrete adequately protects reinforcing steel from corrosion.

Concrete problems, such as excessive deflection, cracking, or spalling may be caused by volume change associated with load effects.



Reinforced Concrete

Simply Supported Reinforced Concrete Beam



Basic Engineering Principles

Reinforced concrete is a structural composite made up of two types of materials:

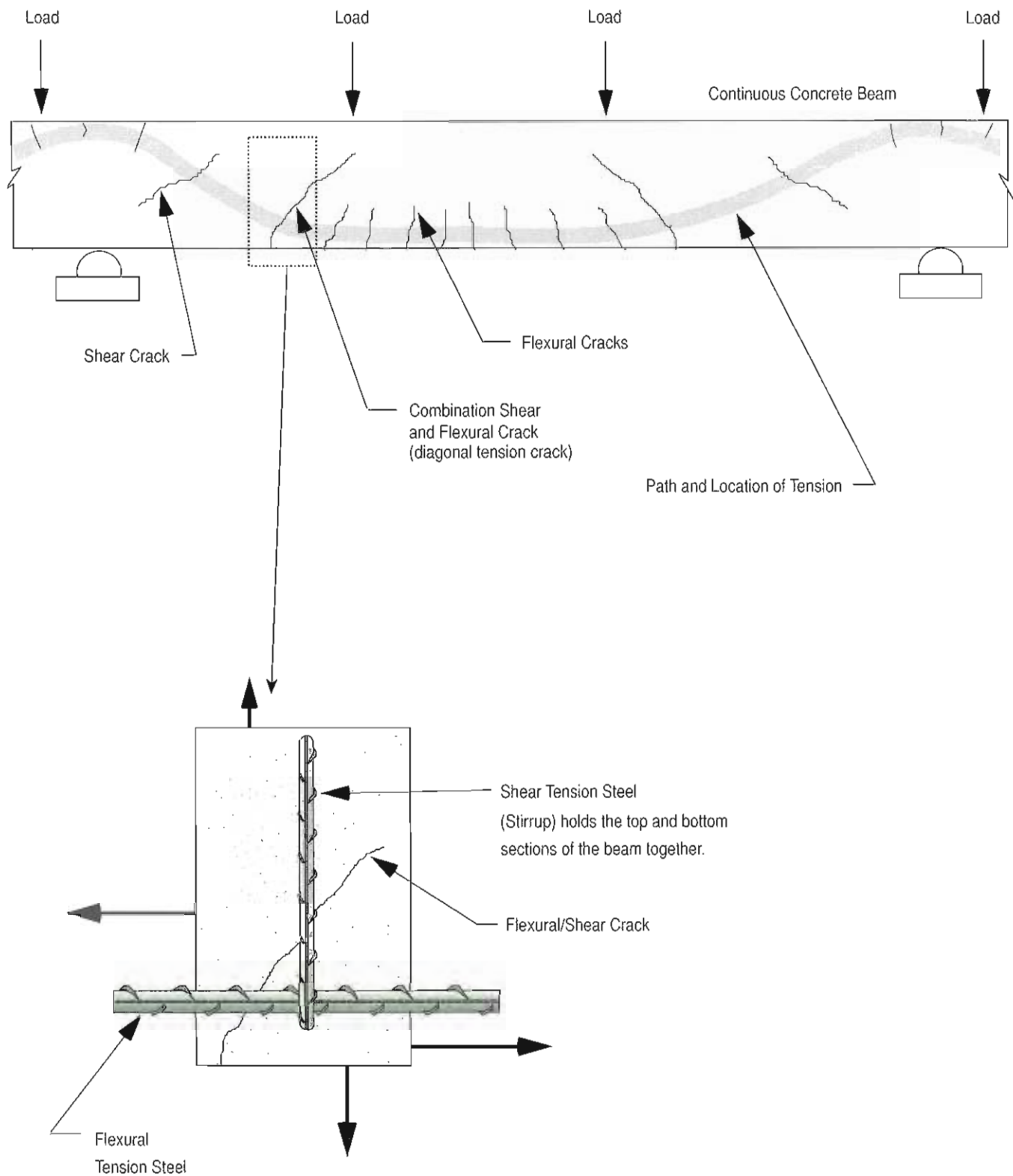
1. Concrete
2. Reinforcing steel

Concrete has excellent compressive properties, but low tensile properties (about 10 percent of its compressive strength). Most concrete members are subject to tension forces. Slabs and beams are the most common members subject to significant tension.

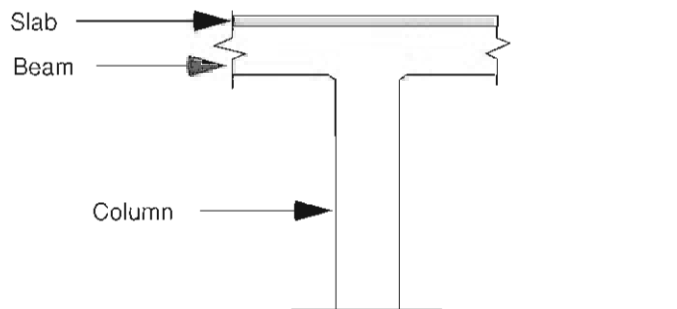
Reinforcing bars are placed in the concrete to carry tension forces. A simply supported beam with loading from the top experiences tension in its bottom (maximum tension at midspan), while compressive forces are acting in the top portion (maximum compression at midspan).

When reinforcing bars are subjected to tension, they stretch. The concrete around the reinforcing bars is consequently subject to tension and stretches. When tension in excess of tensile strength of concrete is reached, transverse cracks may appear near the reinforcing bars (unless prestressed).

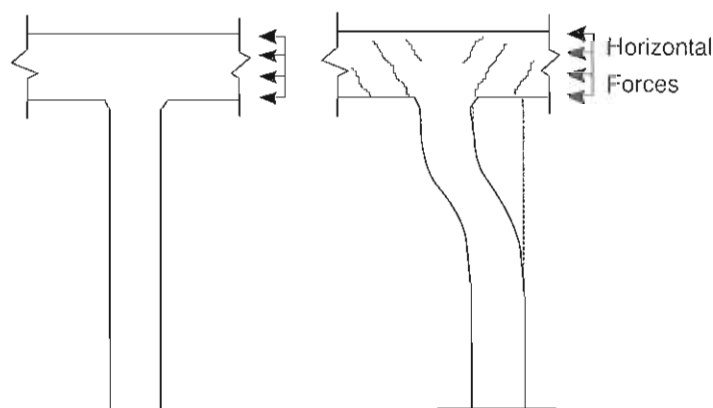
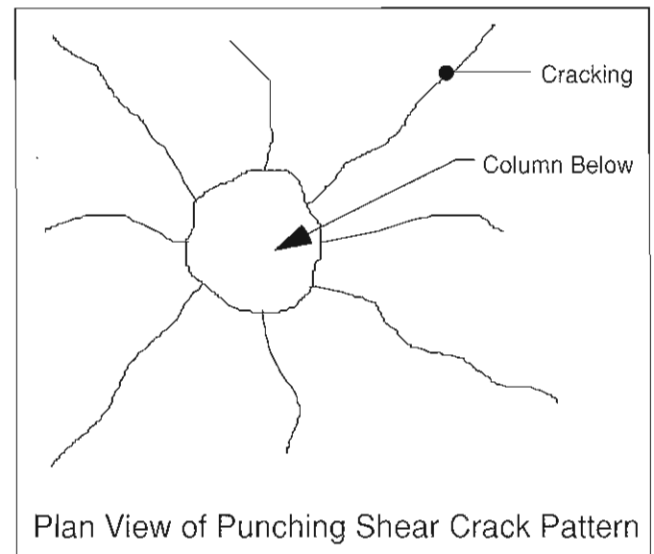
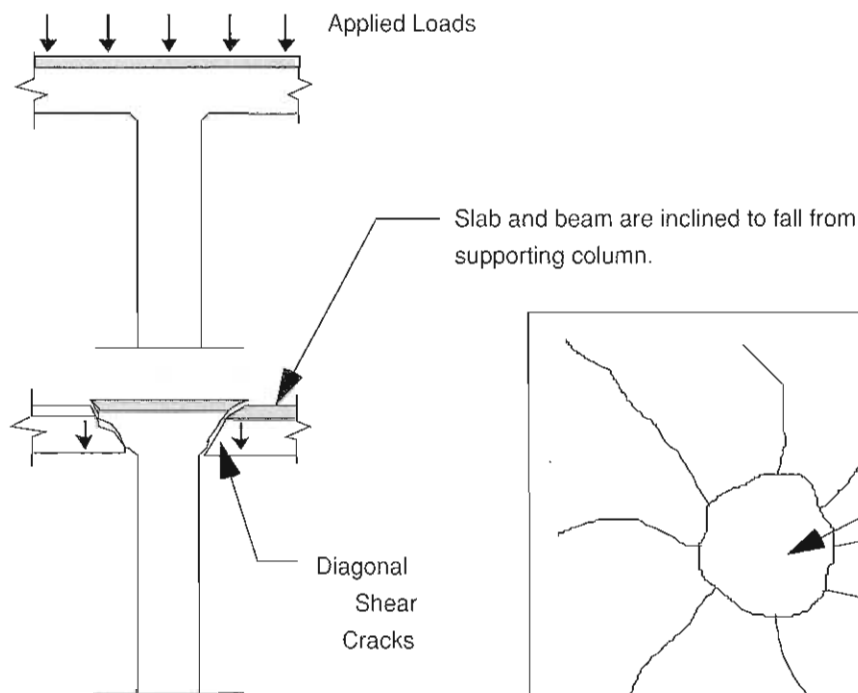
Cracking Modes: Continuous Spans



Slab/Beam-to-Column Shear



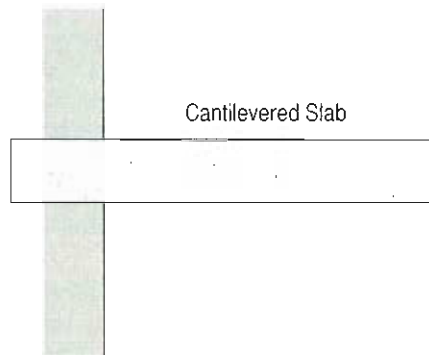
Column connections to slabs and beams experience considerable shear stress. Excessive stress produces cracks in the beams and in the surrounding slab.



Column/beam shear cracking at connections can be caused by horizontal movement. Horizontal forces can accumulate from:

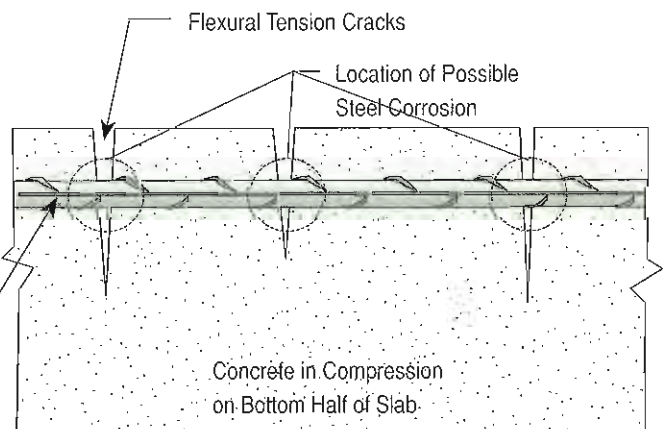
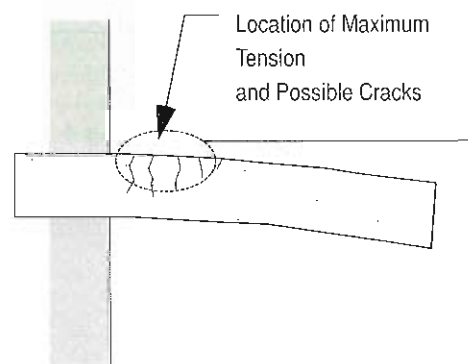
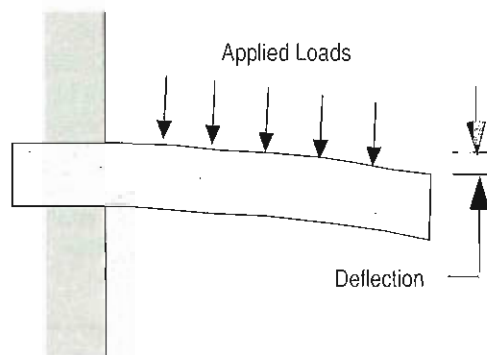
1. Volume changes caused by temperature changes.
2. Elastic shortening caused by post-tension forces.
3. Foundation movements caused by settlement or earthquakes.

Cantilevered Members



Cantilevered members are supported only on one side (balcony slabs are a typical example). Tension forces are acting in the member's top portion (top portion tension is also known as *negative moment*). Tension is greatest at the member's fixed end. Tension forces are carried by the reinforcing steel located in the top portion of the member. Two critical factors should be considered when using cantilevered members:

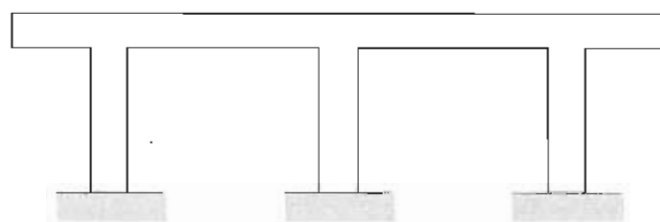
1. The negative moment steel must be placed in the correct position near the member's top surface. Improper placement of the reinforcing steel may result in bending failure of a structural member.
2. Tension cracks that develop over the negative moment steel are natural canyons for moisture and other corrosion-inducing substances. Heavy corrosion results in section loss and causes proportional loss in tension capacity. Yielding of reinforcing steel may result in hinging and complete failure.



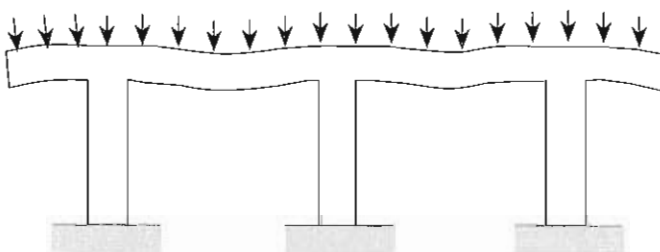
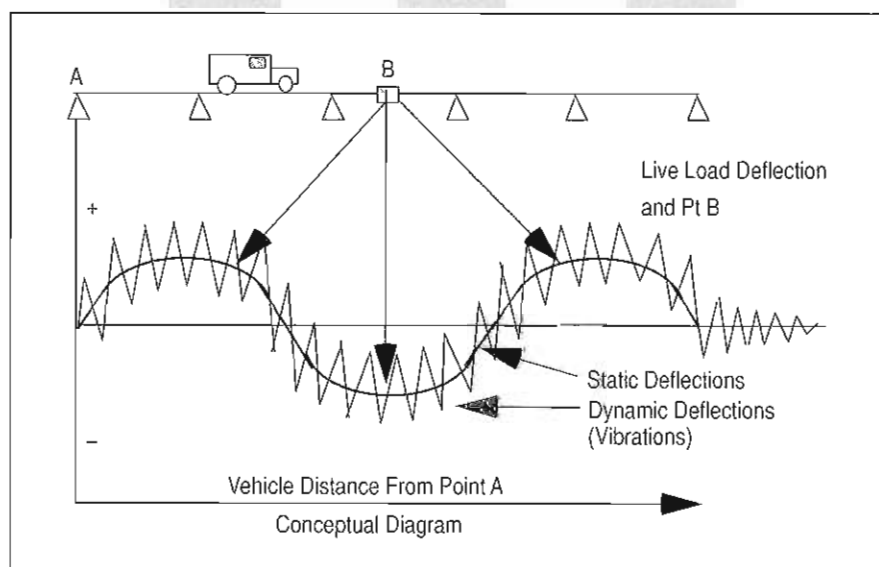
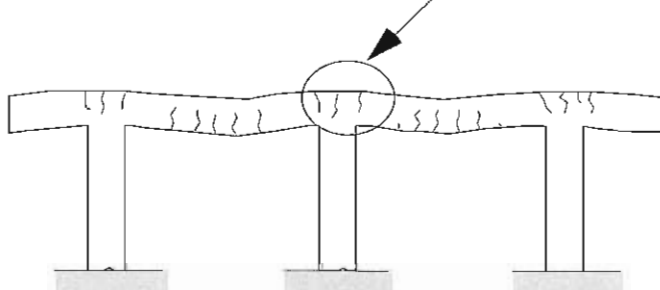
Note: Reinforcing steel must be located in upper portion of member to properly carry tension loads.

Continuous Structures

Continuous Concrete Frame



Applied Loading

Negative Moment Area
Possible Tension Cracks

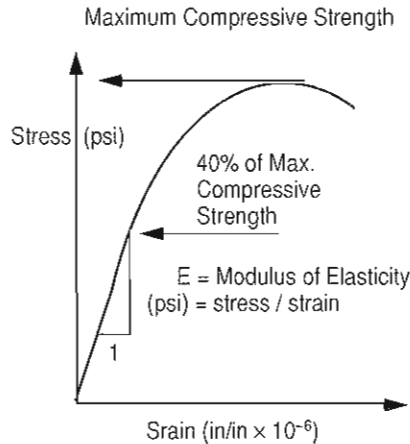
Most cast-in-place structures are designed as continuous members. Unlike simple spans, continuous spans transfer load to adjacent spans. For static loadings, tension stresses usually occur at the bottom (positive moment), at midspan, and at the top (negative moment) over supports.

Concrete in negative moment areas (tensile zone) may be subject to tension cracking. For example, in cantilevered construction, these cracks provide direct access for moisture and other corrosion-inducing substances into the concrete. *Continuous structures* such as parking and bridge decks are also affected by moving loads, which change the stress distribution in adjacent spans, thereby causing reversal deflections and vibrations. These reversal deflections and vibrations at breaks in the structure (expansion joints) may pose maintenance problems for connecting joint systems.

Typical Deflection: 5-Span Continuous Bridge

Repeated deflection reversals occur at Point B, both while the vehicle is on the bridge and just after the vehicle has left the bridge. Continued stress reversals and vibrations can induce cracking, and widen and deepen existing cracks. Cracking is aggravated by increases in span deflection. Cracking occurs in planes of weakness, particularly along the uppermost transverse reinforcement.

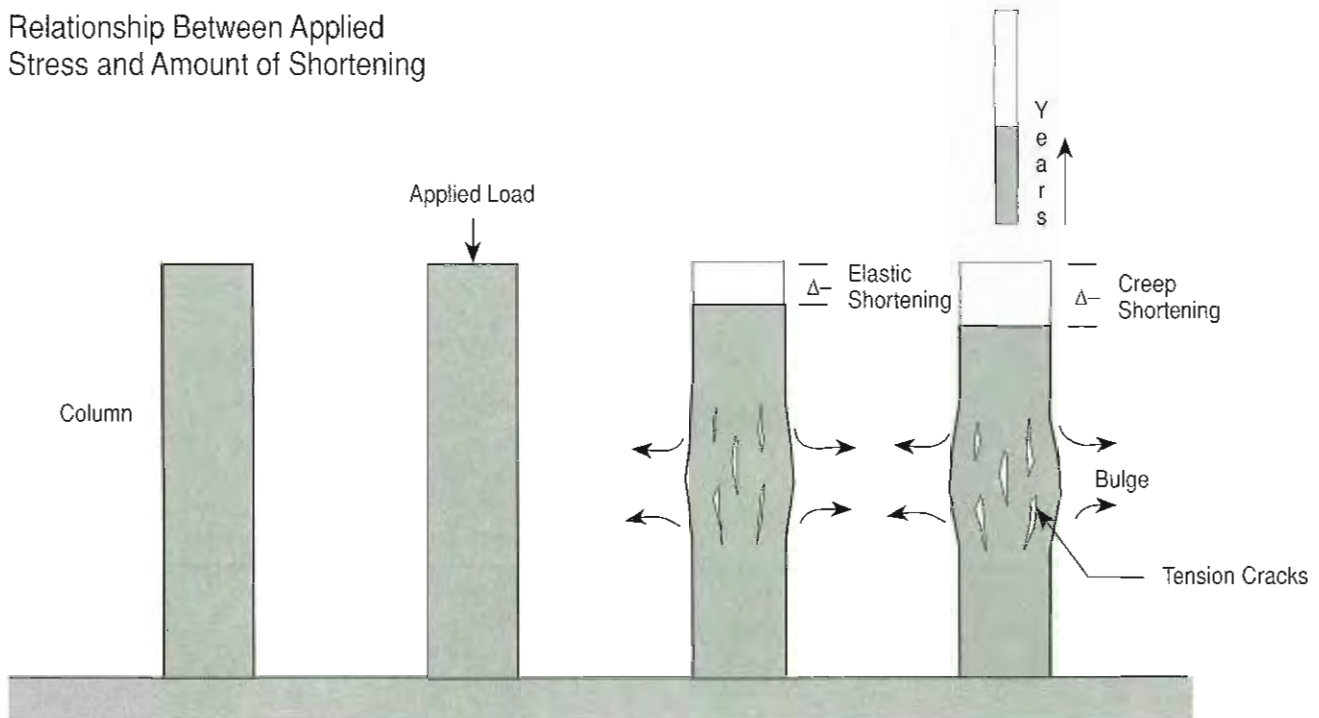
Columns



Columns are designed to carry vertical loads. Concrete, like all materials, stretches (lengthens) under tension, and compresses (shortens) under compression. When concrete is compressed, the member shortens (vertical strain) and bulges (horizontal strain). Horizontal strain is equal to vertical strain times *Poisson's Ratio* (0.1–0.2). The bulge generates tension forces that are restrained by steel reinforcement (column ties). Shortening of columns consists of three components:

1. **Elastic shortening.** Elastic shortening occurs as soon as loads are applied, and is equal to stress (psi) divided by E (*elastic modulus*).
2. **Creep shortening.** Creep shortening occurs over time and is affected by constant stress and long-term loss of moisture (*concrete maturity*).
3. **Drying shrinkage.** Drying shrinkage occurs over time with loss of moisture and is a time-dependent process.

Relationship Between Applied Stress and Amount of Shortening



Working Example: Reinforced concrete column in 500'(153m) tall building under sustained service stress of 1500 psi(10.3MPa) will shorten 8"(204mm) (2.5"(64mm) elastic, 2.5"(64mm) drying shrinkage, 0.5"(12mm) other).

Note: Bulge shown is exaggerated. Crack is shown to demonstrate tensile stress. Column ties resist tension stress.

Post-Tensioned Members

Post-Tensioned Frame



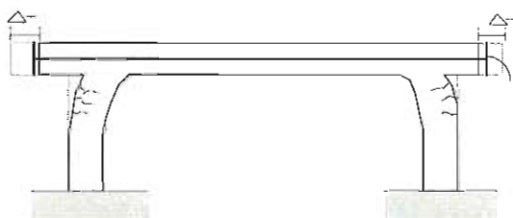
Strands are tensioned, compressing the concrete.



Elastic shortening takes place after stressing.



Additional shortening occurs as a result of creep and drying shrinkage



Post-tensioning of cast-in-place concrete is an effective method of producing durable, efficient structures. The member is compressed with high-tensile steel strands. The strands are jacked from one end of the member, and slippage of the strand through the concrete is allowed with grease and sheathing. The stretching of the strands compresses the concrete to offset any tension stress from future service loads. The lack of tension in the concrete reduces the potential for tension cracking.

Upon stressing, the concrete shortens. This is known as *elastic shortening*. The amount of elastic shortening depends upon the modulus of elasticity (E) and the unit stress to which the concrete is compressed. After stressing, long-term shortening, known as *creep*, will take place. It may take over 1500 days to reach ultimate creep.

Restrained Volume Change

A common problem in post-tensioned structures is lack of design consideration of volume changes in members caused by elastic and plastic (creep) shortening. Short columns in parking structures with opposing post-tensioned framing are ideal locations

for stress relief. The column designed for vertical loads is subject to horizontal pulling in opposite directions, thereby causing severe shear cracking. The shear is also aggravated by diurnal solar heating if the structure is directly exposed to the sun.

Working Example

Length of beam = 60' (18.3 m)

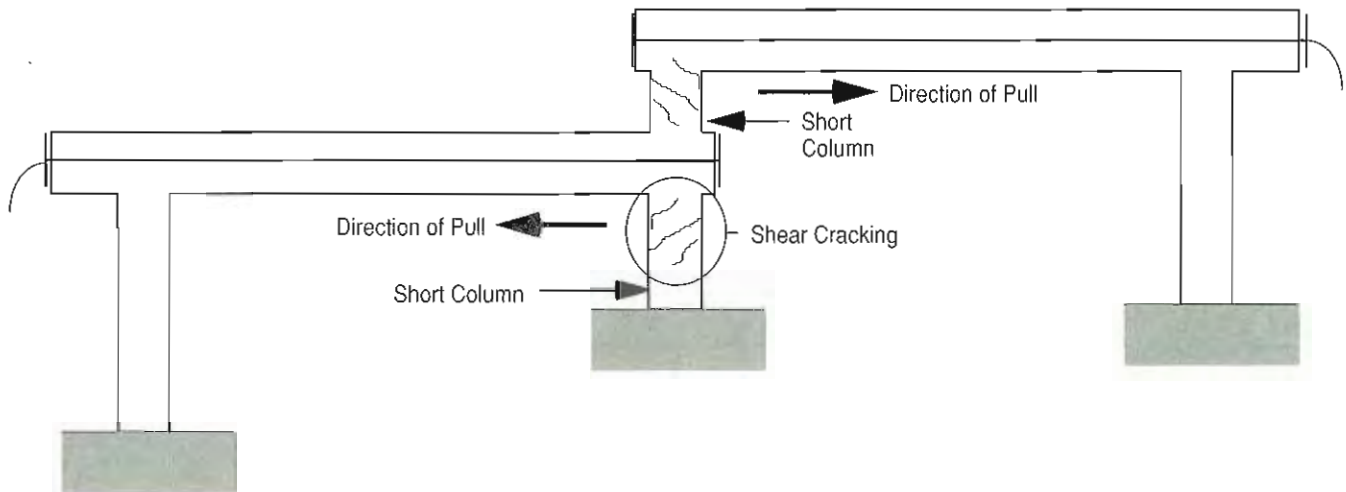
E = 4,000,000 psi (2.8×10^4 MPa)

Compression = 1,000 psi (6.9 MPa)

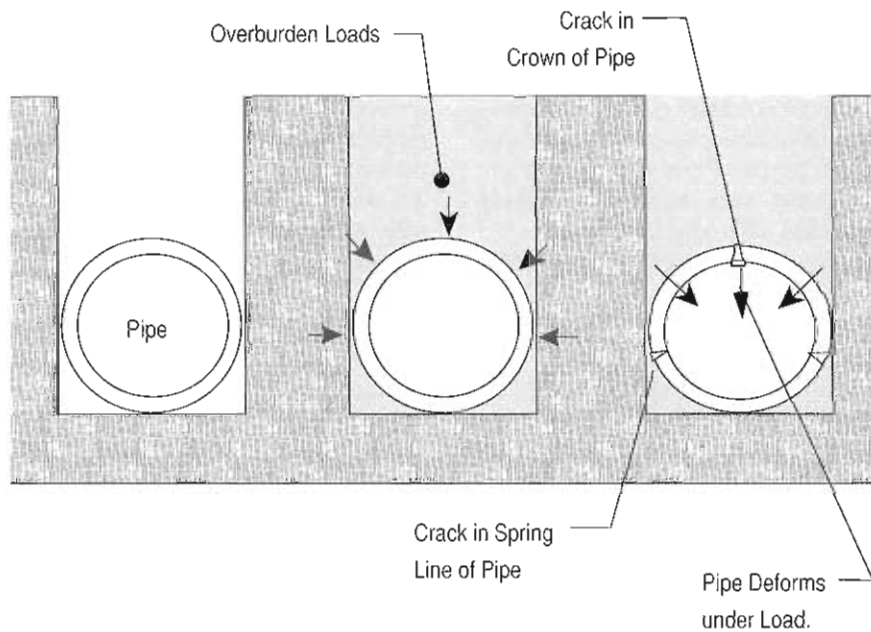
Elastic shortening = 0.18" (4.6 mm) = $\text{stress}/E \times L$
= $(1000 \text{ psi}/4,000,000 \text{ psi}) \times (60' \times 12")$

Creep shortening = 0.36" (9.1 mm) = 0.18" (4.6 mm) \times 2.0 (Creep Coefficient)

Creep + Elastic = 0.54" = 0.36" (9.1 mm) + 0.18" (4.6 mm)



Cylindrical Structures



Buried Pipe

Buried pipes are loaded with surrounding backfill and overburden. Nonuniform loads surrounding the pipe may result in deformation of the pipe. Loads on top may exceed the load on the pipe's underside. The pipe is compressed in the vertical axis and bulges along the horizontal axis. Cracks may develop, forming hinges at three possible locations: the crown (top of pipe), and at the two spring line locations (side of pipe).

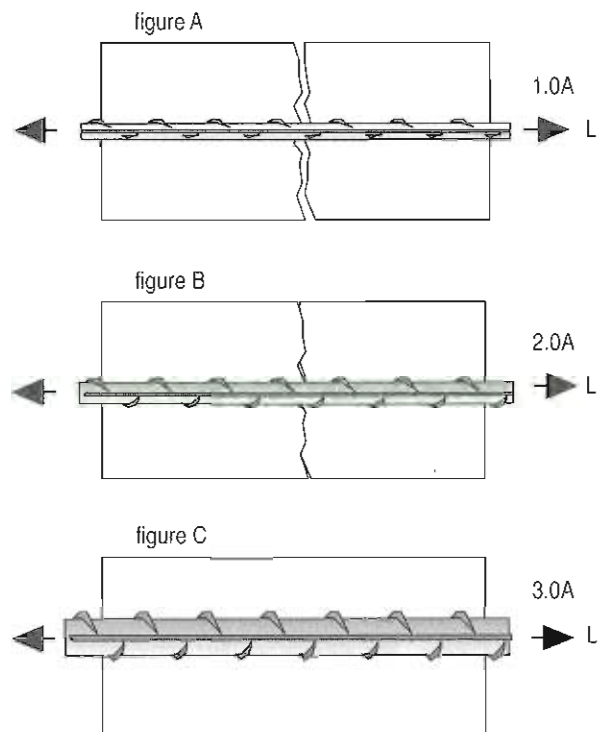
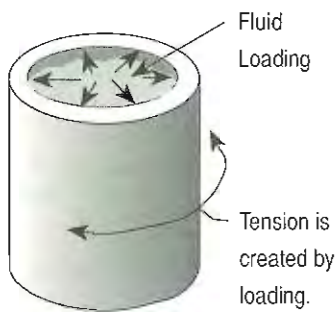
Tanks

Tanks are constructed to hold liquids and flowable solids. The loads imposed on the tank are proportional to the material's density and height of liquid in the tank. Pressure is greatest at the bottom and zero at the top surface. Internal pressure pushes against the tank wall, creating tension. The tension forces must be carried by the reinforcing steel that circles the tank. The amount of stress in the reinforcing steel dictates how well the steel holds the concrete together, thereby preventing cracking.

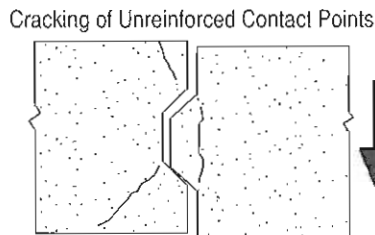
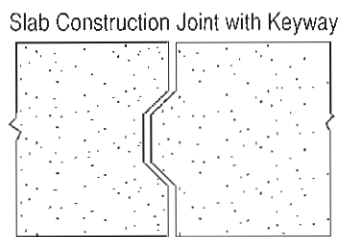
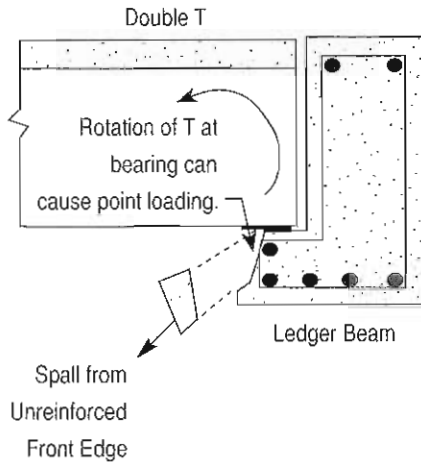
Example:

The tensile stress in a reinforced concrete tank wall is carried by reinforcement. Given three configurations on the right, all have equal tensile loads (L), but each configuration has rebars of a different diameter and cross sectional area (A). All bars have equal modulus of elasticity. The stress level is $L/1.0A$ in Fig. A, $L/2.0A$ in Fig. B, and $L/3.0A$ in Fig. C. Each bar will elongate proportional to the stress level. The bar in Fig. A will elongate three times the elongation of the bar shown in Fig. C. The more elongation, the more likely it is that the concrete will crack.

ACI 350R-89, Section 2.5 recommends a minimum of 0.28 percent and a maximum of 0.60 percent shrinkage and temperature reinforcement, depending upon the grade of steel and length between "shrinkage-dissipating" joints.



Connections



Contact Loading

In every structure, individual components come into contact. Precast structures are comprised of many components, each interacting with others. Point loading of contact points is quite common, often resulting in excessive tension and shear. Extremities and edges of members subject to point loading are free to crack and spall when tension stresses exceed the tensile capacity of the concrete. Embedded reinforcing steel is not a factor, since most steel is embedded below the contact point.

Precast *double-T stems* resting on ledger beams often point load the front edge of the non-reinforced portion of the ledger beam. Point loading can be a result of rotation (diurnal solar heating) or length change from seasonal thermal changes.

Slabs cast on grade are separated by construction joints. Shear transfer between slabs at these joints are locations where point loading can occur. Rolling loads place the joint edges into contact with one another, often creating stresses that spall and crack the non-reinforced portions.

Another common problem with pavement slabs is the filling of the open joint with non-compressible debris, preventing the joint from undergoing free thermal expansion. Restrained volume change can induce very high shear, compression and tension stresses.

Working Example: Dirt accumulation in joint restrains thermal movement.

$E = 4,000,000$ psi (Modulus of Elasticity), unit strain = 0.0003 (thermal coef. x temp. change)

Stress = 1200 psi = $E \times \text{Unit Strain} = 4,000,000 \text{ psi} \times 0.0003 \text{ in/in} = \text{compressive stress}$



Debris fills joint . . . then temperature rises, causing compressive forces to develop.

Additional Sources of Information

Wang, Chee-Kia and Salmon, C.G., Reinforced Concrete Design, Thomas Y. Cromwell, Harper & Row Publishers, New York.

Notes on ACI 318-89, Building Code Requirements for Reinforced Concrete with Design Applications, Portland Cement Association, 1990.

ACI 350R-89, Environmental Engineering Concrete Structures, ACI Manual of Concrete Practice, Part 4, 1991.

Section 6: Faulty Workmanship— Designer, Detailer, Contractor

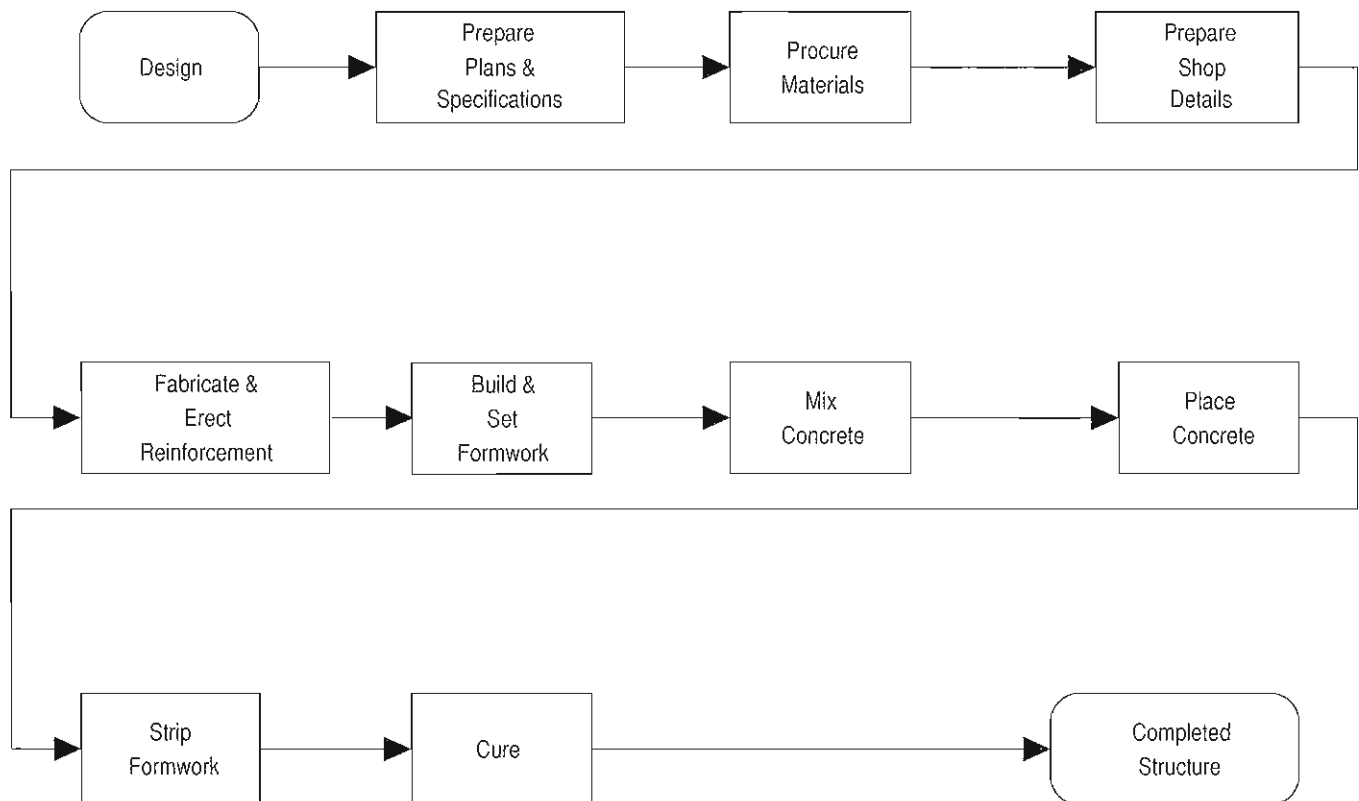
The following topics are covered in this section:

Improper Reinforcing Steel Placement
Improper Post-Tensioned Cable Drape
Improper Reinforcing Steel Placement:
Highly Congested
Improper Bar Detailing: Location of
Stirrups
Premature Removal of Forms
Improper Column Form Placement
Cold Joints
Segregation
Improper Grades of Slab Surfaces
Construction Tolerances
Plastic Settlement (Subsidence) Cracking
Plastic Shrinkage Cracking
Honeycomb—Rock Pockets

Faulty Workmanship: Introduction

Methods used to construct concrete structures are different from methods used in other types of construction. Concrete is one of the few materials in which raw ingredients are brought together at, or near, the construction site, where they are mixed, placed and molded into a final product. There are so many variables affecting the production of concrete that there is always a

potential for something to go wrong. Every building process includes a sequence of necessary step-by-step operations—from conceptual plan to finished structure. Following is a flow chart of a typical building process. Each box represents a category of problems that can arise in the building process.



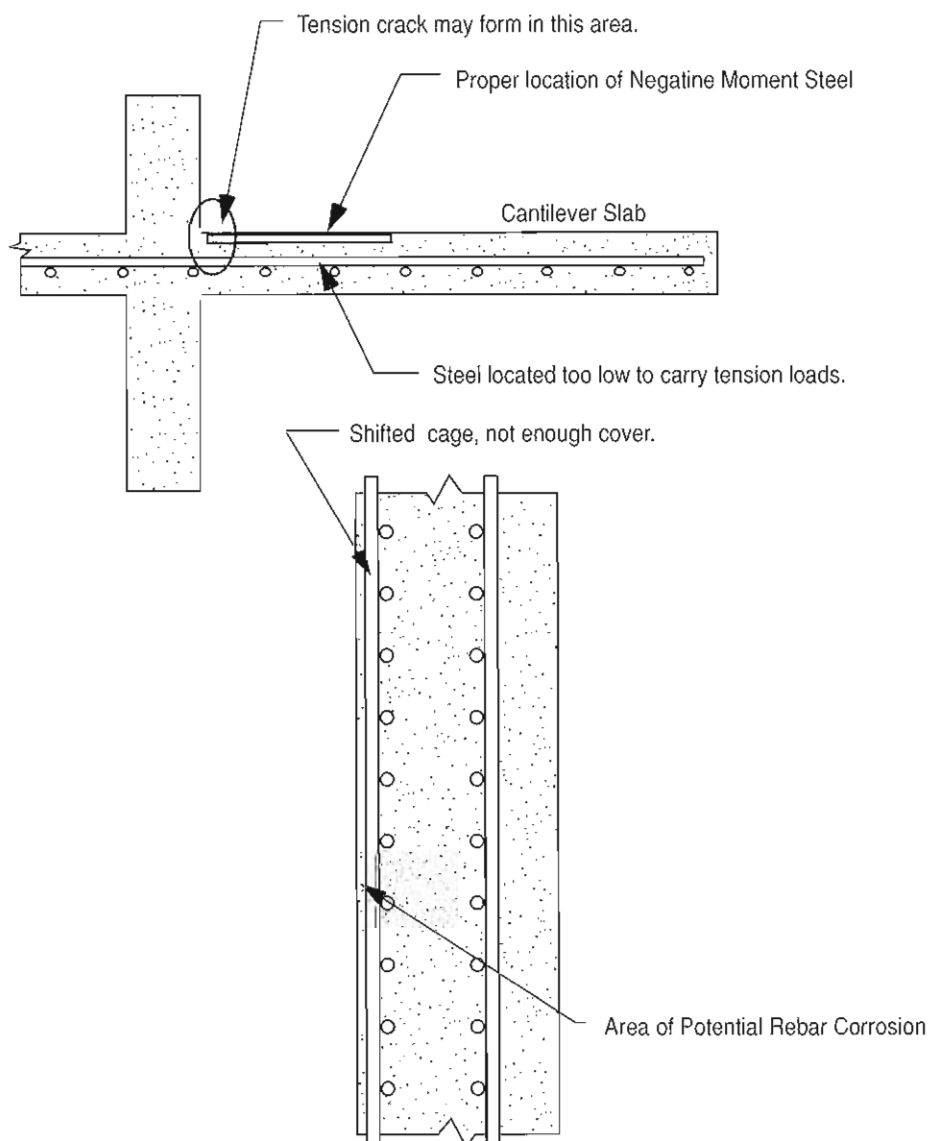
Improper Reinforcing Steel Placement

ACI-required concrete cover for corrosion protection

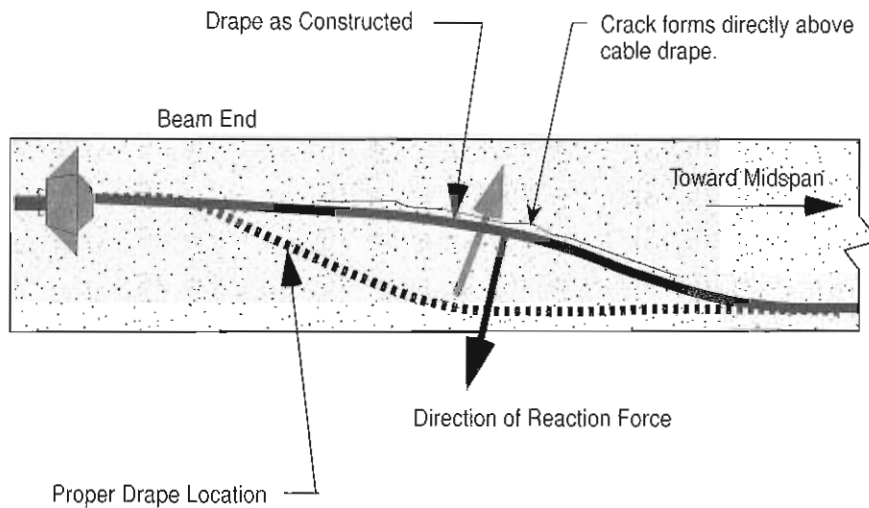
Condition	Cover required in. (mm)
Concrete deposited on the ground	3 (76)
<i>Formed surfaces exposed to weather</i>	
bars > #6	2 (51)
bars < #5	1.5 (38)
<i>Formed surfaces not exposed to weather</i>	
beams, girders, columns	1.5 (38)
slabs, walls, joists	
bars < #11	0.75 (19)
bars #14, #18	1.5 (38)

There are two important reasons to control the proper location of reinforcing steel in structures. First, reinforcing steel is placed in concrete to carry tensile loads, and if the steel is misplaced, the concrete may not be able to carry the tensile loads. Cantilevered slabs, and negative moment areas near columns pose particular risk. Second,

reinforcing steel requires adequate concrete cover to protect it from *corrosion*. The alkalinity of the concrete is a natural corrosive inhibitor. If the concrete cover is inadequate, it will not provide the necessary long-term protection. Shifted reinforcing bar cages in walls or beams may also cause the reinforcing steel to lose proper cover.

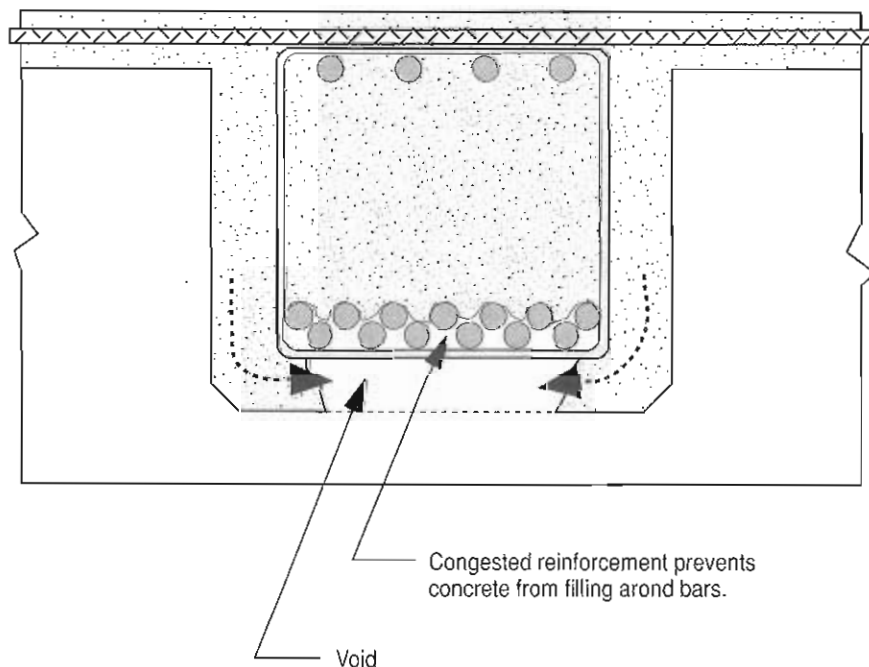


Improper Post-Tensioned Cable Drape



Correct placement of post-tension cable is critical to achieve the designed structural load-carrying capacity. Improper placement may result in tension stress, causing the concrete to crack.

Improper Reinforcing Steel Placement



Highly Congested Reinforcement

Beams and columns are usually heavily reinforced members. Lap splices require overlaps of bars and may result in a mat of steel that concrete mix cannot pass through during placement and consolidation. The result is either a visible, or worse, a latent void around the reinforcement.

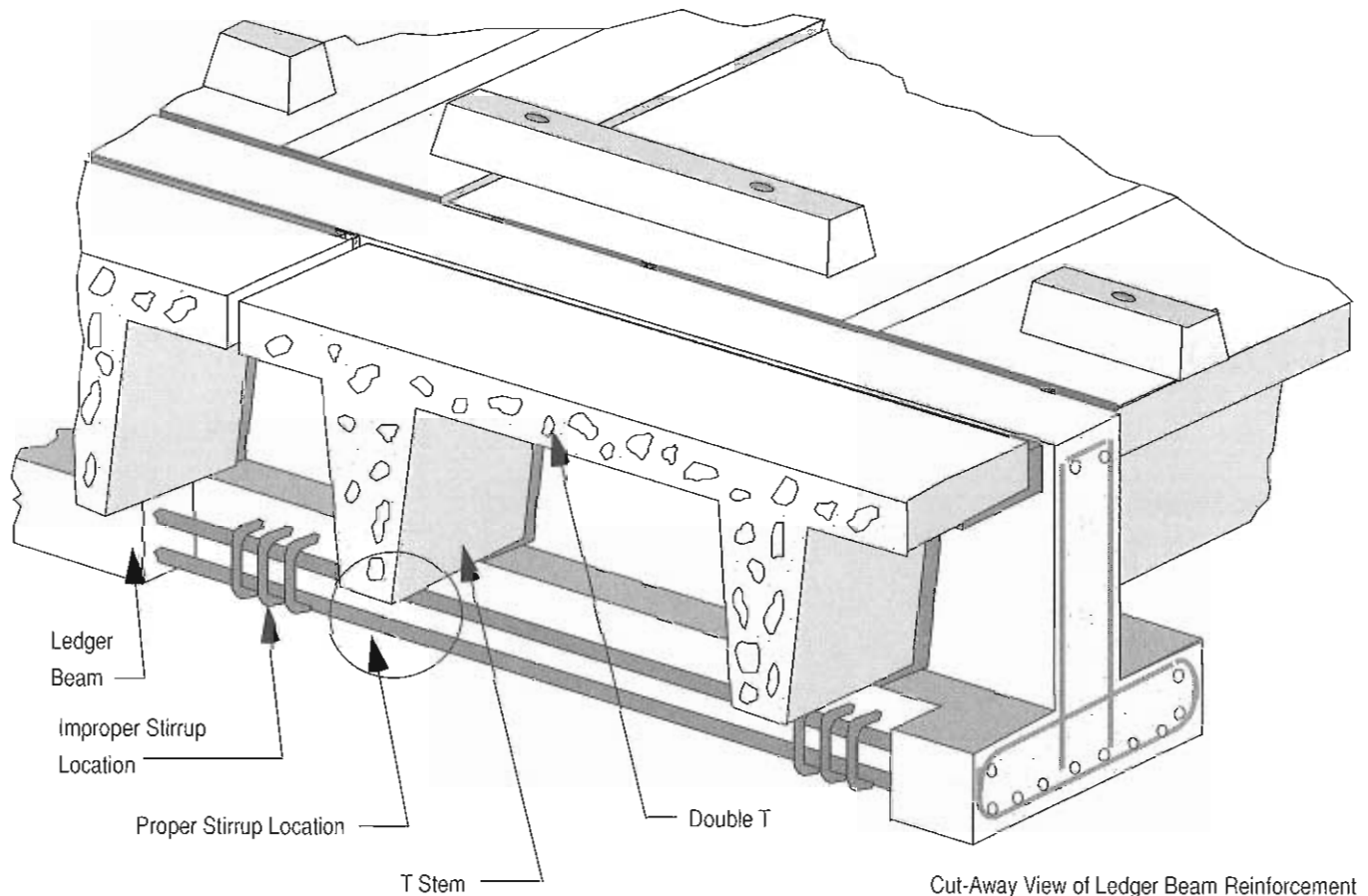
Improper Bar Placement

Location of Stirrups

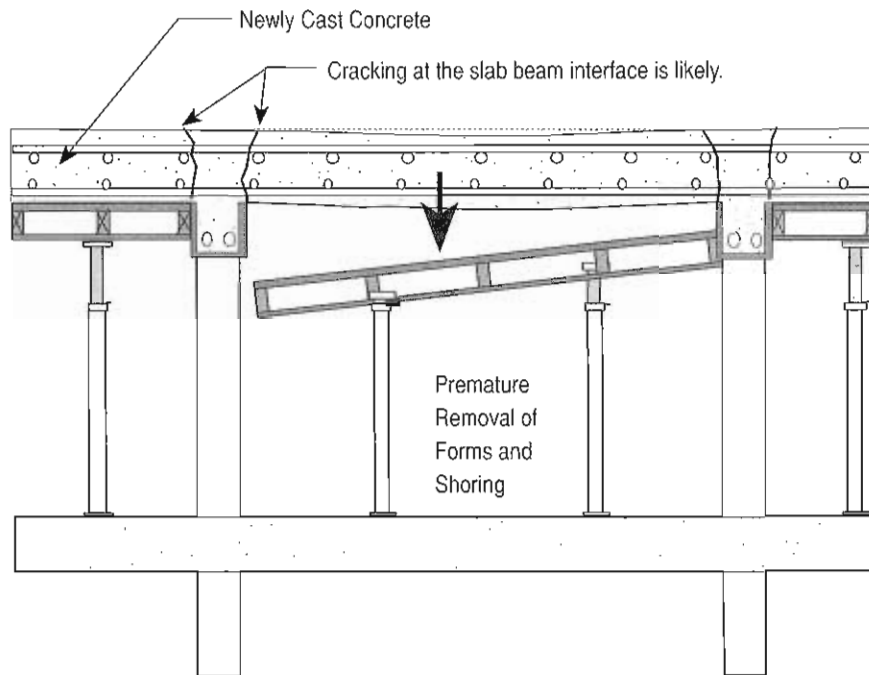
Double-T members are a common element used in this type of construction. T's are generally supported by an inverted T-beam or ledger beam. The cantilevered portion of the beam supports the double-T's stem. Critical

forces in the cantilever are taken up by stirrups directly beneath the stem location. Improper placement of the stirrups may result in a failure of the ledger beam support, and the double-T may then drop.

Typical Precast Parking Structure Configuration

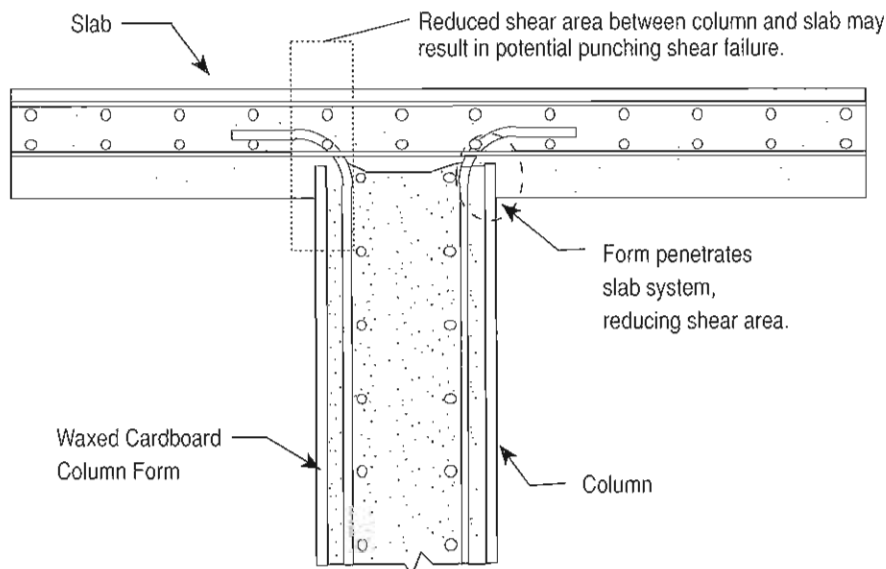


Premature Removal of Forms



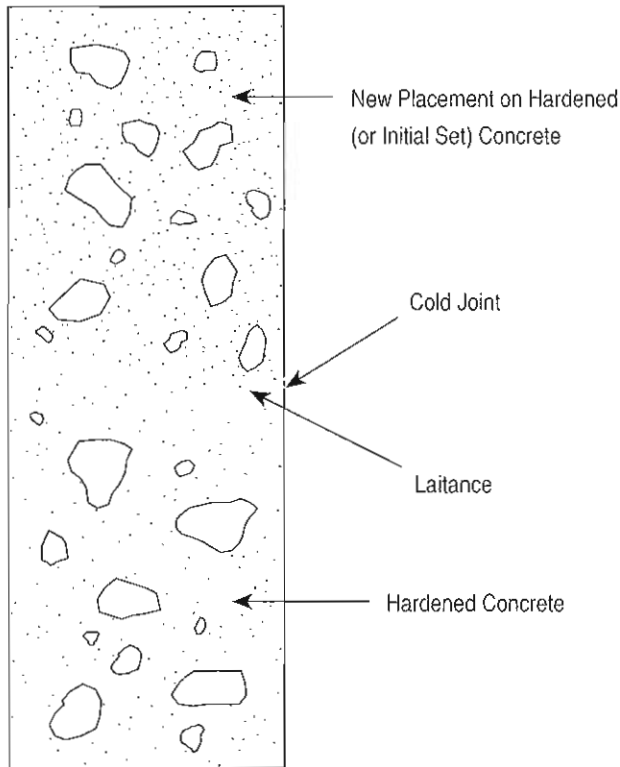
Removal of forms (including shoring) before the concrete has reached its proper strength may result in compression and tension stresses, causing cracking, deflection, and possible collapse.

Improper Column Form Placement



Cardboard cylinder forms are widely used in the construction of round columns. Typically, columns are cast prior to the placement of the slab/beam formwork. The exact elevation of the slab/beam bottom may not be precisely determined when the columns are cast. If the column is cast too tall and penetrates the slab/beam concrete, critical shear stresses may occur because of inadequate shear capacity area between the column and the slab/beam. The smooth form surface may not provide adequate shear transfer.

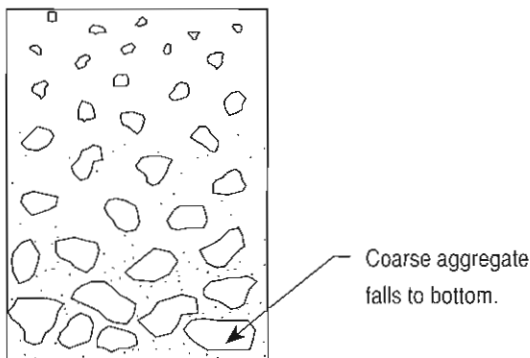
Cold Joints



Cold joints are places of discontinuity within a member where concrete may not tightly bond to itself. Cold joints may form between planned placements and within a placement. Some construction placement procedures require multiple lifts. A dam is a good example, as are tall walls. To achieve proper bond and water-tightness, the surface of hardened concrete must be free of dirt, debris, and *laitance*. Proper cleaning and placement procedures sometimes are not followed or are very difficult to achieve. The result is a weak connection between placements that could result in weakness or leakage at a later date.

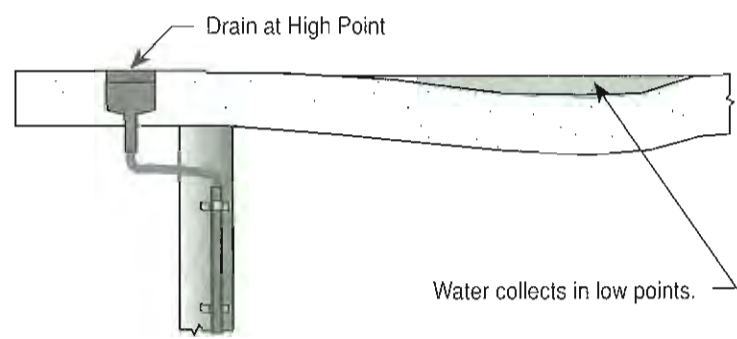
The other type of cold joint may occur within a planned placement if a part of the concrete in one placement sets, and then the rest of the concrete is placed on it. During the set, laitances form, providing for a weakened plane. Leakage may occur when the structure is put into service.

Segregation



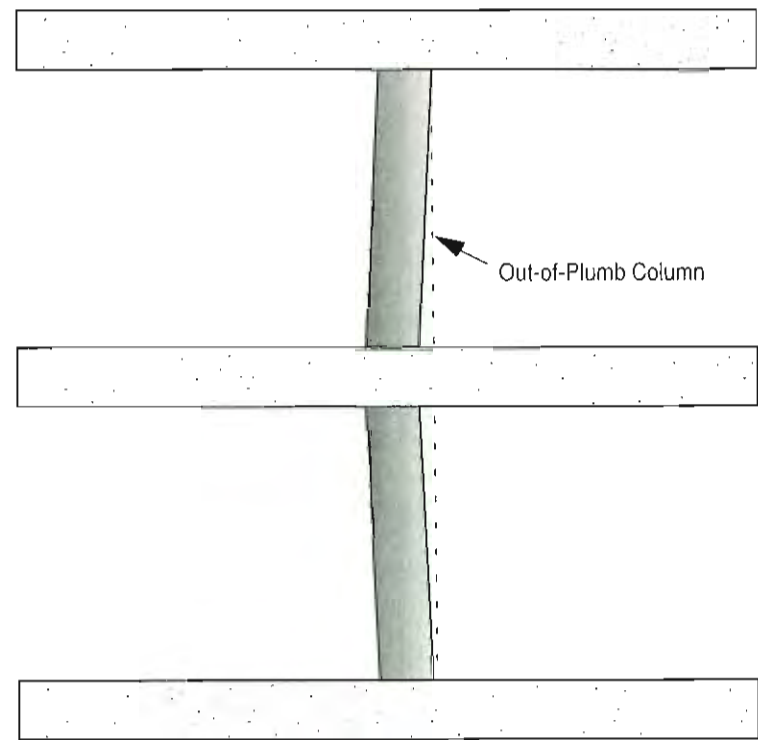
Segregation of concrete results in nonuniform distribution of its constituents. High slump mixes, incorrect methods of handling concrete, and over-vibration are causes of this problem. Segregation causes upper surfaces to have excessive paste and fines, and may have excessive water-cement ratio. The resultant concrete may lack acceptable durability.

Improper Grades of Slab Surfaces



Slabs requiring drainage for proper runoff need special attention. Drains should be at low, not high points. Proper slope-to-pitch for quick runoff is important to prevent deterioration and leakage within the structure. Standing water provides concrete with the potential for saturation, the worst condition for a freeze-thaw cycle. The quicker the water runs off the structure, the less leakage can occur through joints and cracks.

Construction Tolerances

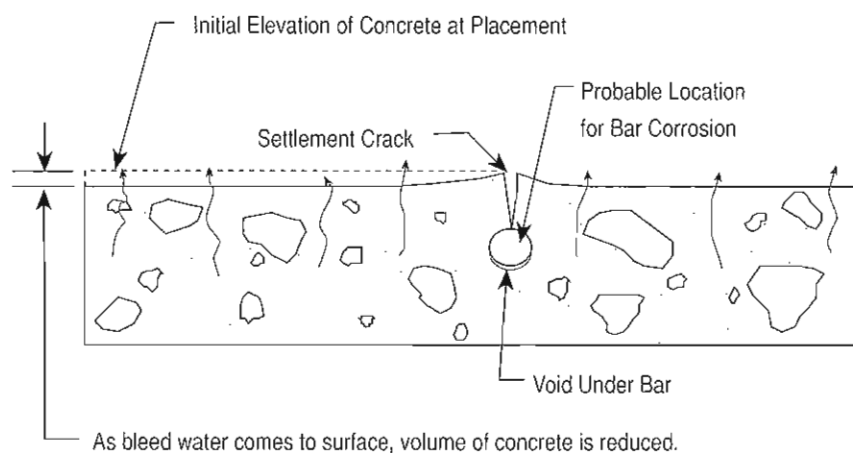


Structural members that are cast out of tolerance pose aesthetic and structural problems. Members cast out of tolerance may have improper concrete cover and cross section, which may produce eccentric loading.

Tolerances for Formed Surfaces

Variation from plumb	in (mm)
any 10' length	1/4 (6)
maximum entire length	1 (25)
Variations from level	
slab soffits 10' length	1/4 (6)
maximum entire length	3/4 (19)
Variations in cross section	
minus	1/4 (6)
plus	1/2 (13)

Plastic Settlement (Subsidence) Cracking



Plastic settlement cracking is caused by the settlement of plastic concrete around fixed reinforcement, leaving a plastic tear above the bar and a possible void beneath the bar. The probability of cracking is a function of:

1. Cover
2. Slump
3. Bar size

Settlement of plastic concrete is caused by:

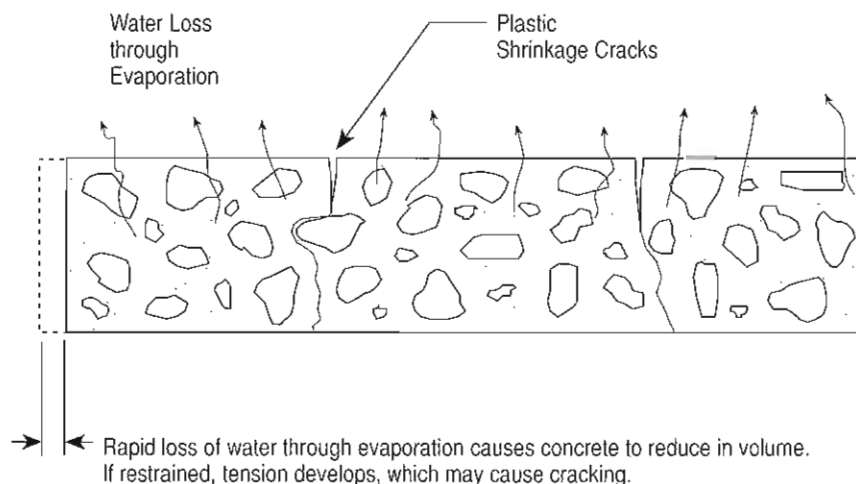
1. Low sand content and high water content
2. Large bars
3. Poor thermal insulation
4. Restraining settlement due to irregular shape
5. Excessive, uneven absorbency
6. Low humidity
7. Insufficient time between top-out of columns and placement of slab and beam
8. Insufficient vibration
9. Movement of formwork

Probability of Subsidence Cracking (%)*

Cover	2" Slump			3" Slump			4" Slump		
	#4	#5	#6	#4	#5	#6	#4	#5	#6
3/4"	80.4	87.8	92.5	91.9	98.7	100	100	100	100
1"	60	71	78.1	73	83.4	89.9	85.2	94.7	100
1 1/2"	18.6	34.5	45.6	31.1	47.7	58.9	44.2	61.1	72
2"	0	1.8	14.1	4.9	12.7	26.3	5.1	24.7	39

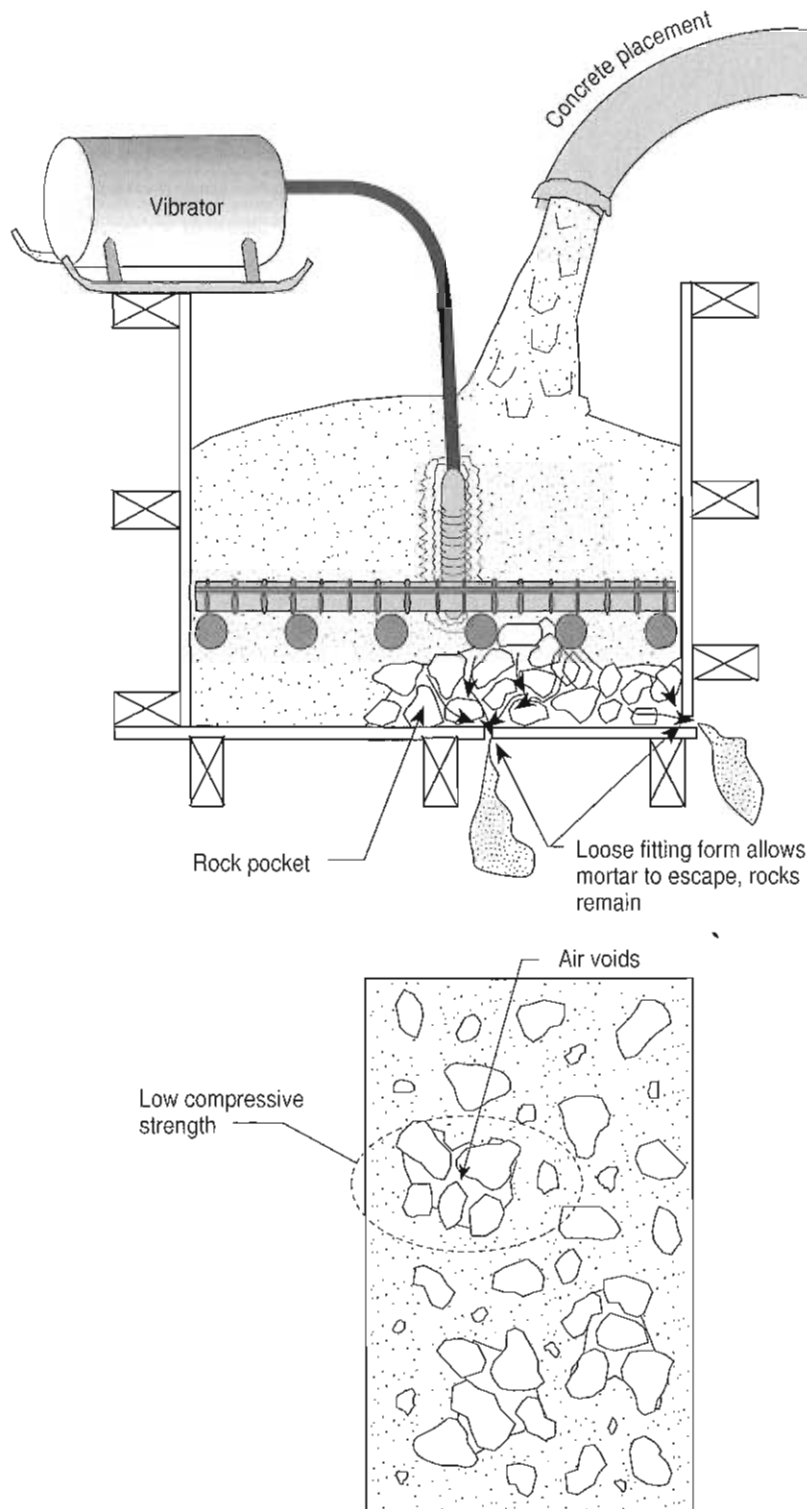
*NCHRP 297, Table 4, p. 11.

Plastic Shrinkage Cracking



Plastic shrinkage is caused by the rapid evaporation of mix water (not bleed water) while the concrete is in its plastic state and in the early stages of initial set. Shrinkage results in cracking when it produces tension stress greater than the stress capacity of the newly placed concrete. Plastic shrinkage cracking rarely fractures aggregate, but separates around the aggregate. Plastic shrinkage cracks may lead to points of thermal and dry shrinkage movement, intensifying the cracking.

Honeycomb and Rock Pockets



Honeycomb is a void left in concrete due to failure of the mortar to effectively fill the spaces among coarse aggregate particles. Rock pockets are generally severe conditions of honeycomb where an excessive volume of aggregate is found.

Primary Causes of Honeycomb

Design of members

- highly congested reinforcement
- narrow section
- internal interference
- reinforcement splices

Forms

- leaking at joints
- severe grout loss

Construction conditions

- reinforcement too close to forms
- high temperature
- accessibility

Properties of fresh concrete

- insufficient fines
- low workability
- early stiffening
- excessive mixing
- aggregate that is too large

Placement

- excessive free-fall
- excessive travel in forms
- lift that is too high
- improper *tremie* or *drop chute*
- segregation

Consolidation

- vibrator too small
- frequency too low
- amplitude too small
- short immersion time
- excessive spacing between insertion
- inadequate penetration

Part Two **Concrete Evaluation**

Part Two

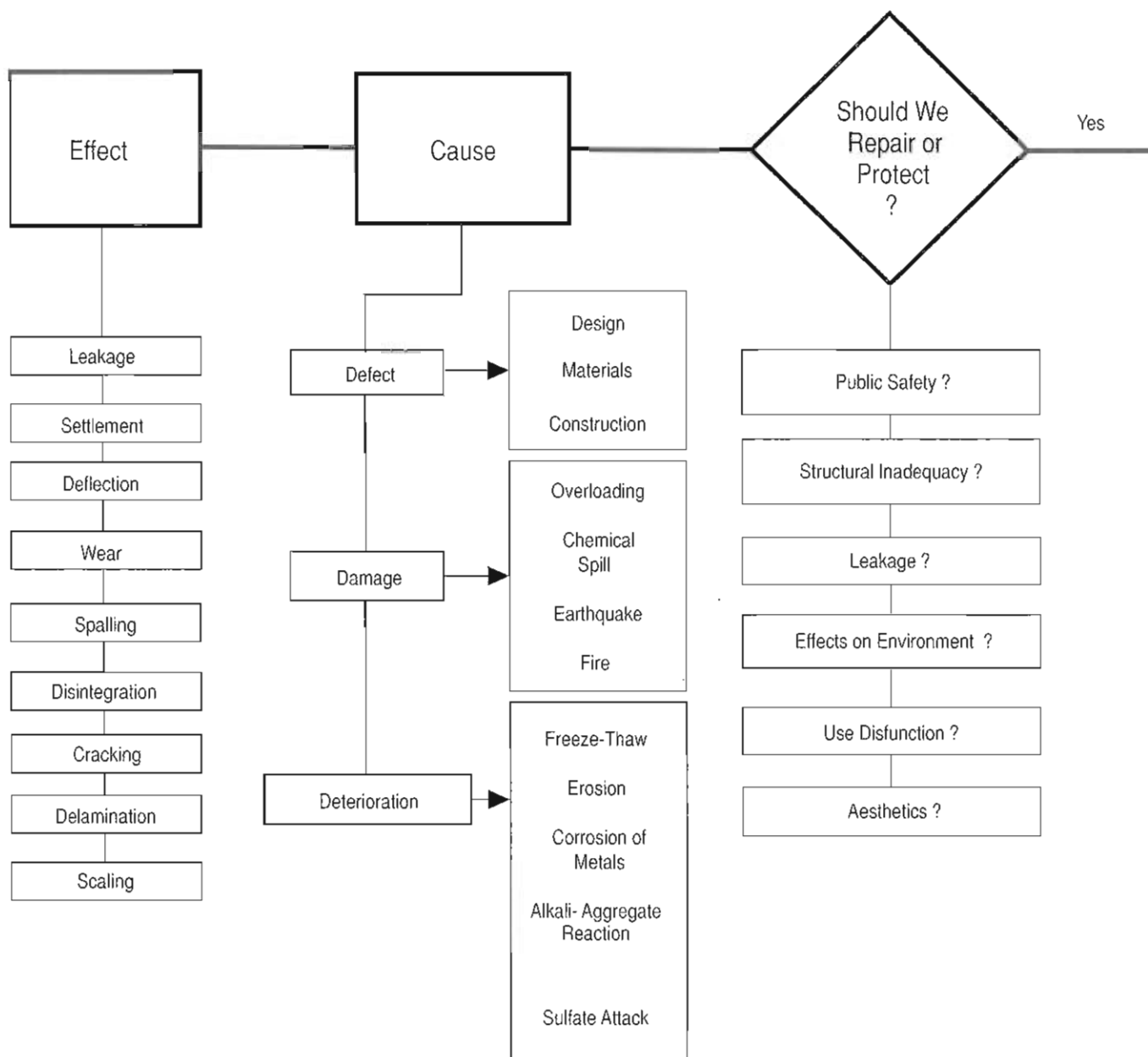
Concrete

Evaluation

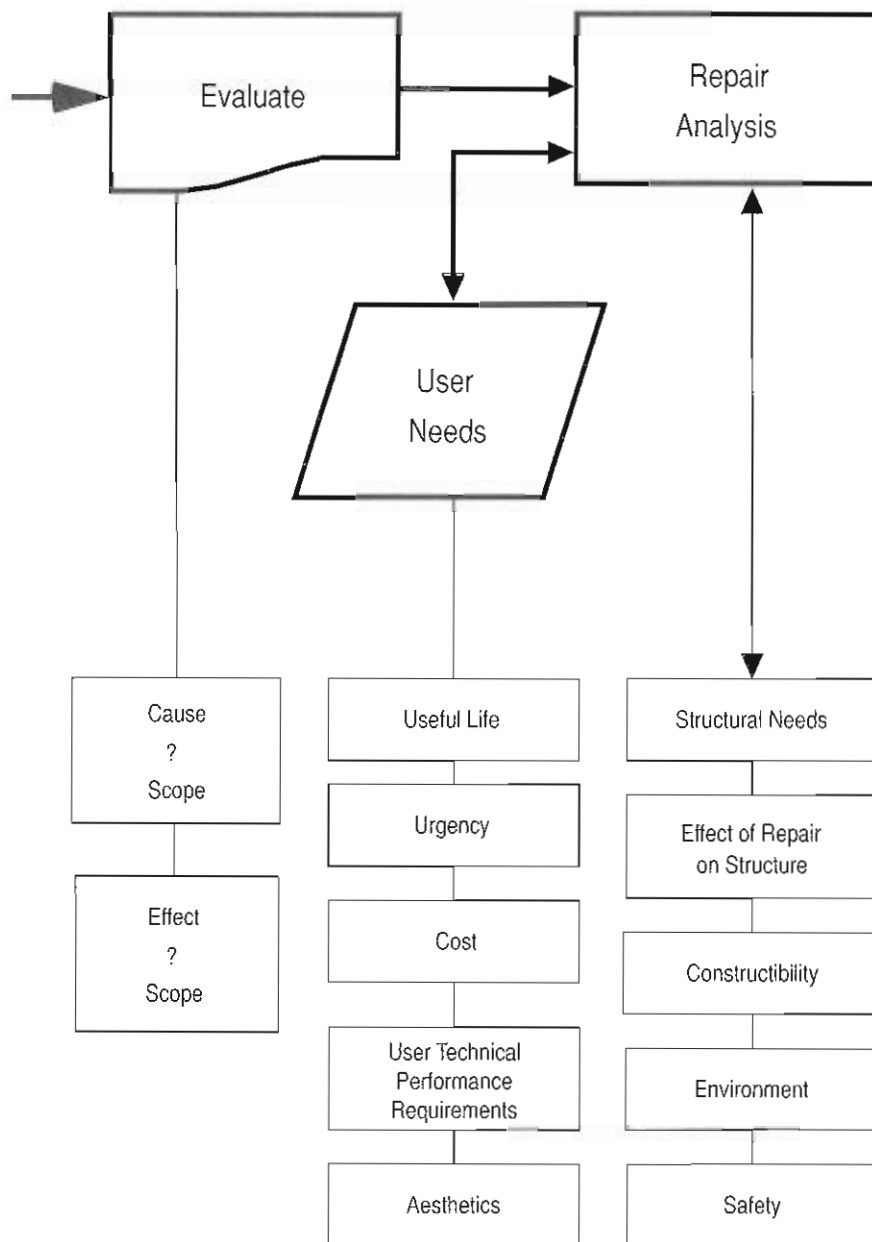
Part Two

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Introduction to Part Two



This Part presents information on how to conduct an evaluation of concrete in an existing structure. A thorough and logical evaluation of the current condition of the structure is the first step of any repair or rehabilitation project.

Concrete can be defective for several reasons, including inadequate design, material selection and/or workmanship. Concrete can also deteriorate or be damaged in use. Consequently, existing reinforced concrete may not be functioning as originally intended and designed. Concrete in a structure has a number of functions. First and foremost, as a structural material, concrete is designed to carry loads: for example, to provide a bearing surface for traffic, including pedestrian and vehicular. Concrete also provides protection to embedded reinforcement. Reinforced concrete is a composite material consisting of concrete and reinforcing steel. The bond between the individual constituents is most critical for the properties of the composite material. Embedded reinforcing steel must be adequately bonded to the surrounding concrete carrying the anticipated design loads.

Disfunction of concrete structures usually occurs in some form of visible distress such as cracking, leaching, spalling, scaling, stains, disintegration, wear, settlement, or deflection. For a more complete description of concrete disfunction, see Part 1, Concrete Behavior.

The evaluation of concrete structures can be either a reactive or proactive process. Generally, evaluation takes place as a result of some visible sign of distress, causing structural and/or durability concerns of poor functional performance, which, in turn, result in safety concerns.

The evaluation process is important in determining such factors as cause of the disfunction and structural safety, and for establishing a general scope of problems found. The following sections will outline the most common methods used to evaluate concrete. Other sources of information on concrete evaluation can be found in the *ACI Manual of Concrete Practice*, ACI 201.1R Guide for Durable Concrete and ACI 207.3R, Practices for Evaluation of Concrete in Existing Massive Structures for Service Conditions.

Testing Methods for Concrete Evaluation

Mechanical Properties	Chemical Make-up	Physical Condition	External Manifestation (behavior)
Compressive Strength -Core testing (1) -Windsor probe (3) -Rebound hammer (2)	Electro-chemical Activity -Half cell potential (9) -Electrical resistivity (10)	Uniformity -Petrographic analysis (11) -Pulse velocity (4) -Windsor probe (3) -Rebound hammer (2) -Core testing (1)	Cracks/spalls -Hammer sounding -Infrared thermography -Impact echo -Pulse velocity (4) -Remote viewing (TV, borescope) -Exploratory removal
Quality of Concrete Ultrasonic pulse velocity(4)	Carbonation Depth -Acid based indicators (Phenolphthalein Solution) -Petrographic analysis (11) -X-ray diffraction -Infrared spectroscopy	Air-Void System (15)	Deflections from Service Loads -Load testing (ACI 437R) -Monitoring movements
Tensile Strength -Pull off testing -Splitting tensile strength (5)	Alkali-Aggregate Reactions -Petrographic analysis (11) -Uranyl (Uranium) Acetate fluorescence method	Delaminations/voids -Hammer sounding -Chain drag -Impact echo -Pulse velocity (4) -Exploratory removal -Remote viewing (TV, Borescope) -Infrared thermography	Movements of Service/Exposure Conditions -Load testing (ACI 437R) -Monitoring movements
Flexural Strength (6) (7)	Chloride Content (12) (13) (14)	Location/Condition of Embedded Metals -Pachometer -Radiography -Ground penetrating radar -Exploratory removal	Leakage -Visual observations -Infrared thermography
Abrasion resistance (8)		Water permeability	Temperature/moisture conditions -Thermocouple -Thermometer
Bond Strength -Pull off testing		Air permeability	External Geometry -Visual observations
		Water absorption (19)	
		Frost & freeze-thaw resistance (16) (17)	
		Resistance to deicing salts (18)	

Note: Figures in parentheses denote number of standard test in Table A

TABLE A. STANDARD TEST METHODS FOR EVALUATING CONCRETE

NO.	DESIGNATION	TITLE
1	ASTM C 42	Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
2	ASTM C 805	Rebound Number of Hardened Concrete
3	ASTM C 803	Penetration Resistance of Hardened Concrete
4	ASTM C 597	Pulse Velocity Through Concrete
5	ASTM C 496	Splitting Tensile Strength of Cylindrical Concrete Specimens
6	ASTM C 78	Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
7	ASTM C 293	Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)
8	ASTM C 418	Abrasion Resistance of Concrete by Sandblasting
9	ASTM C 876	Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete
10	ASTM D 3633	Electrical Resistivity of Membrane-Pavement Systems
11	ASTM C 856	Standard Practice for Petrographic Examination of Hardened Concrete
12	AASHTO T 259	Resistance of Concrete to Chloride Ion Penetration
13	AASHTO T 260	Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials
14	AASHTO T 277	Rapid Determination of the Chloride Permeability of Concrete
15	ASTM C 457	Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete
16	ASTM C 666	Resistance of Concrete to Rapid Freezing and Thawing
17	ASTM C 671	Critical Dilation of Concrete Specimens Subjected to Freezing
18	ASTM C 672	Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
19	ASTM C 642	Specific Gravity, Absorption, and Voids in Hardened Concrete

Condition Survey Procedure

The steps in a typical evaluation of a concrete structure are:

1. Visual inspection (walk-through)
2. Review of engineering data
 - a. Design and construction documentation
 - b. Operation and maintenance records
 - c. Concrete (including materials used) records
 - d. Periodic inspection reports
3. Condition survey
 - a. Mapping of the various deficiencies
 - b. Monitoring
 - c. Joint survey
 - d. Sampling and testing
 - e. Nondestructive testing
 - f. Structural analysis

4. Final evaluation

5. Condition survey report

The results of any evaluation, especially determining the cause and scope of the problem, are only as accurate as the understanding and effort applied to the process. A cursory review or walk-through inspection will not produce as accurate an evaluation as an in-depth, detailed investigation involving the necessary mapping, sampling, testing and exploratory efforts.

▼

Section 1:

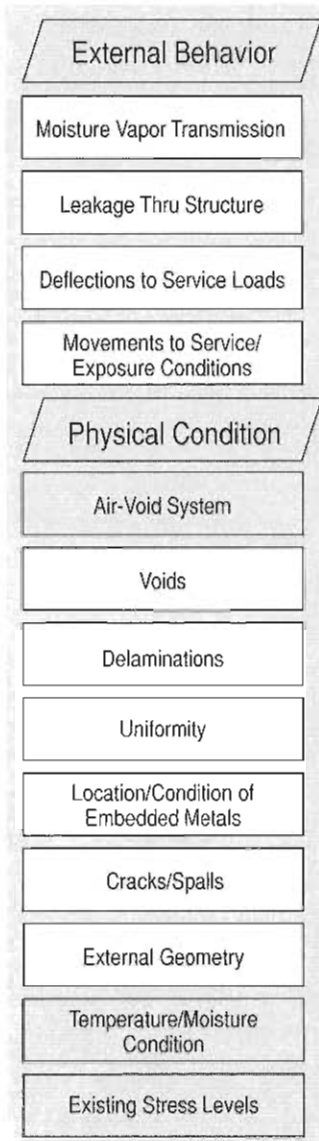
Service and Exposure Conditions

Concrete evaluation is not limited to studies of its physical condition, mechanical properties, chemical make-up, and external manifestation. Understanding its interaction with the environment is equally important. In many cases, the cause of a concrete problem

is related to a service or exposure condition. The catalog of service and exposure conditions presented below is a listing of some of the conditions to be considered when analyzing concrete behavior.

Temperature	Moisture	Chemical	Loading
High-Low	Relative Humidity Range	Type	Moving
Frequency	Contact Type: Immersion, runoff	Concentration	Static
Duration	Frequency	Form: Gas, Liquid, Solid	Impact
Freeze-thaw Cycles	Duration	Frequency	Vibration
Solar Exposure		Duration	Form: Gas, Liquid, Solid
Protection at Early Age ?			Size/Magnitude
			Frequency
			Duration

Section 2: Visual and Exploratory Investigation

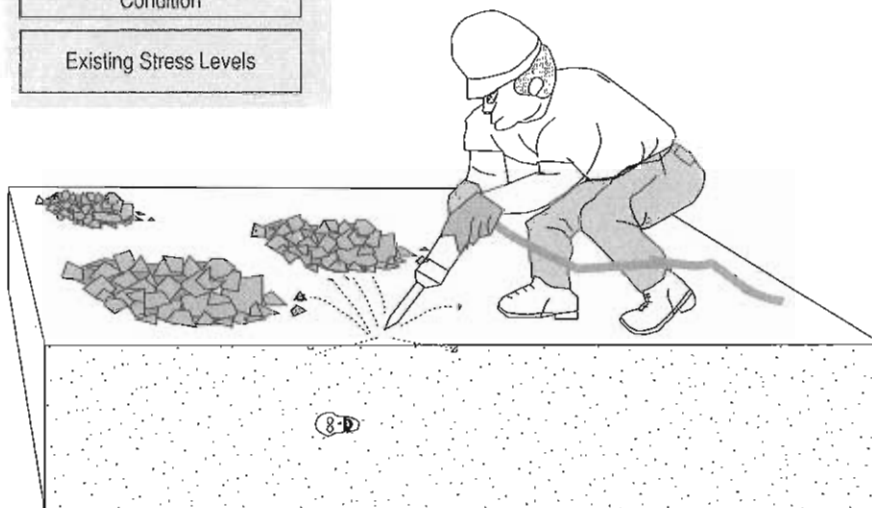


Any thorough investigation starts with a visual review of conditions. Key indicators of problems are:

1. Cracking (crazing)
2. Surface distress
 - a. Spalling
 - b. Disintegration of the surface
 - c. Surface honeycomb
 - d. Scaling
3. Water leakage
 - a. Surface dampness
 - b. Seepage or leakage through joints or cracks
4. Movements
 - a. Deflections
 - b. Heaving
 - c. Settlement
5. Metal corrosion
 - a. Rust staining
 - b. Exposed post-tension cable strands
 - c. Exposed reinforcing bars
6. Miscellaneous
 - a. Blistering membranes and coatings
 - b. Ponding of water
 - c. Discoloration

Visual examination, mapping the location of problems on paper, and then reviewing these along with as-built drawings and construction records can provide a general scope of the problems and possible clues to causes.

Visual examination often results in many questions regarding the extent and details of deterioration/distress. A useful way to answer these questions is the exploratory removal of concrete to expose hidden elements. Chipping and core drilling are the most common exploratory methods.



Section 3: Locating Delaminated Concrete

Physical Condition
Air Void System
Voids
Delaminations
Uniformity
Location/Condition of Embedded Metals
Cracks/Spalls
External Geometry
Temperature/Moisture Condition
Existing Stress Levels

Acoustical Emissions and Thermography Methods

Sounding of concrete with a hammer provides a low-cost, accurate method for identifying delaminated areas. When striking areas of delaminated concrete, the sound changes from "ping" to a hollow sounding "puck." Boundaries of delaminations can easily be determined by sounding areas surrounding the first "puck" until "pings" are heard.

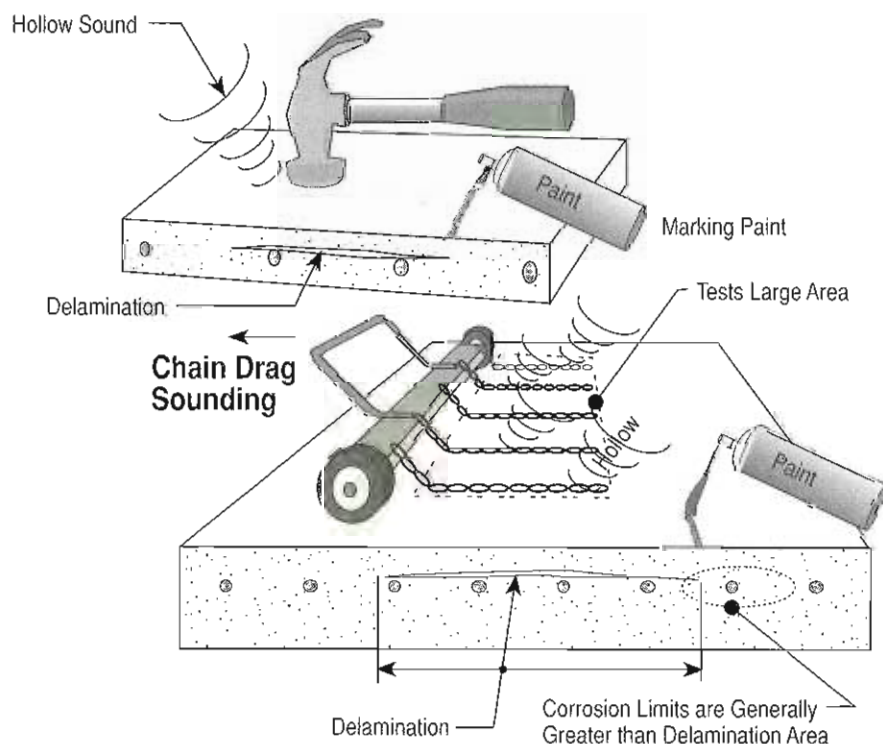
Hammer-sounding of large areas generally proves to be extremely time consuming. More productive sounding methods are available when working with horizontal surfaces. Chain dragging accomplishes the same result as hammer-sounding. As the chain is dragged across a concrete surface, a distinctly different sound is heard when it crosses over a delaminated area.

Automated electronic systems are also available, eliminating the need for an operator to listen for differences in acoustic emissions. However, these methods have proved to give only a general picture of the areas of delamination. Consequently, they should be used only for general assessment, not for the detailed layout required for reconstruction.

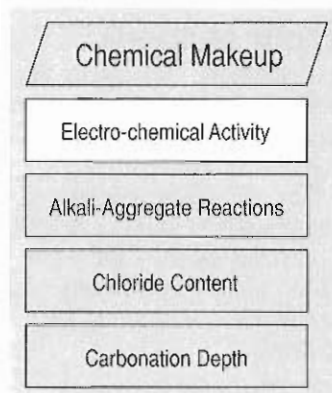
Infrared thermography is a useful method of detecting delaminations in bridge decks. This method is also used for other concrete components exposed to direct sunlight. The method works on the principle that, as the concrete heats and cools, there is substantial thermal gradient within the concrete because concrete is a poor conductor of heat. Delaminations and other discontinuities interrupt the heat transfer through the concrete. These defects cause a higher surface temperature during periods of heating, and a lower surface temperature than the surrounding concrete during periods of cooling. The equipment can record and identify areas of delamination and indicate depth of delaminations below the surface.

Note: Area of corrosion activity in concrete is generally larger than area of delamination.

Hammer Sounding



Section 4: Corrosion Activity Measurements



Corrosion of reinforcement is the electrochemical degradation of steel in concrete. It occurs when the passivity of the steel is destroyed by carbonation or by chloride ions and electrochemical cells develop. When steel corrodes in concrete, a potential difference exists between the anodic half-cell areas and the cathodic half-cell areas on the steel.¹ This difference can be detected by placing a copper-copper sulfate half-cell on the surface of the concrete and measuring the potential differences between the reinforcing steel and a wet sponge on the concrete surface. The reference cell connects the concrete surface to a high-impedance voltmeter, which is also connected electrically to the reinforcing steel mat. The voltmeter then reads the potential difference at the test location. These readings are taken on a grid basis and converted into potential gradient mapping.

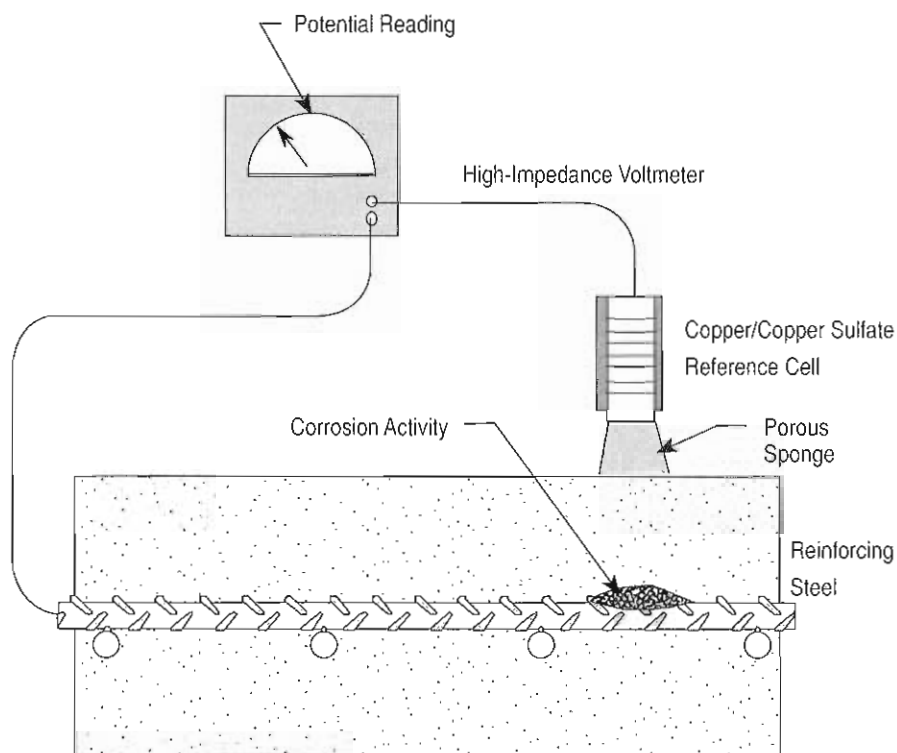
It is generally agreed that the half-cell potential measurements can be interpreted as follows²:

- Less negative than -0.20 volts indicates a 90 percent probability of no corrosion.
- Between -0.20 and -0.35 volts, corrosion activity is uncertain.
- More negative than -0.35 volts is indicative of a greater than 90 percent probability that corrosion is occurring.

If positive readings are obtained, it usually means that insufficient moisture is available in the concrete and the readings are not valid. These tests do not indicate the rate of corrosion: the measurements only manifest the potential for corrosion at the time of measurement.

These half-cell methods cannot detect corrosion in post-tensioned strands, nor can they detect corrosion when reinforcing steel is discontinuous from the voltmeter. However, half-cell measurements are often useful because they are easy to perform, and results can be delivered quickly at relatively low costs.

A full description of the above test procedure and equipment is detailed in ASTM C 876, Half Cell Potentials of Reinforcing Steel in Concrete.



¹NCHRP Report 140, Durability of Prestressed Concrete Highway Structures, TRB, 1988, p.22.

²NCHRP Report 312, Condition Surveys of Concrete Bridge Components—User's Manual, TRB, 1985, p. 35.

Section 5: Chloride Content

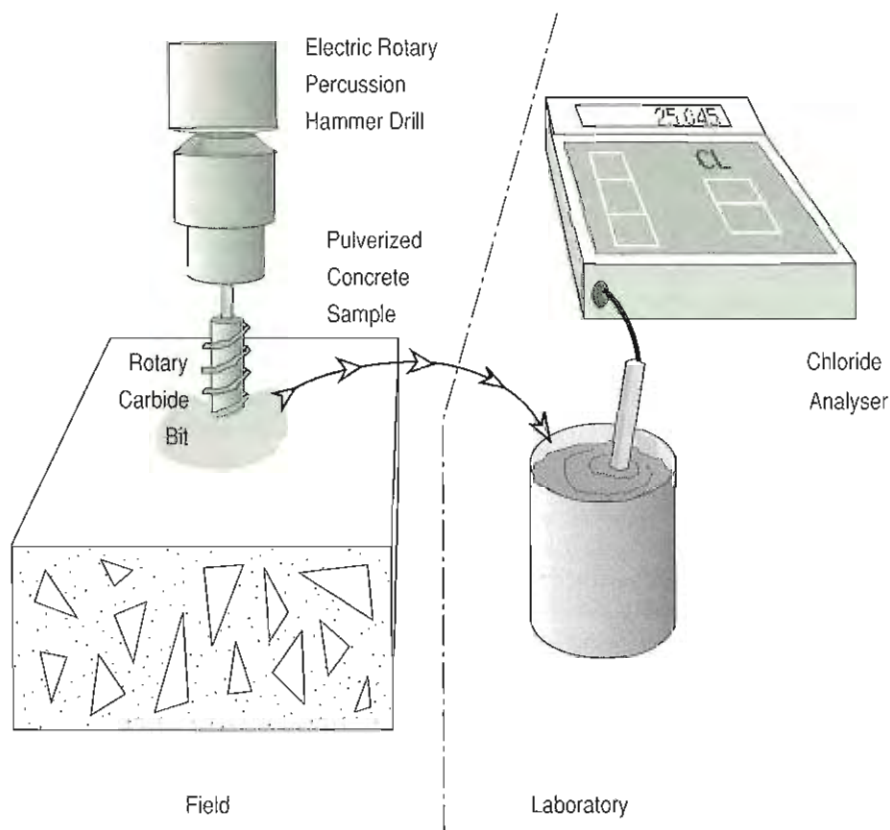
Chemical Makeup
Electro-chemical Activity
Alkali Aggregate Reactions
Chloride Content
Carbonation Depth

Because the amount of chlorides present in reinforced concrete can greatly affect its performance, chloride-ion content evaluation is an important testing method. It is done by taking a sample of concrete from the structure, either by drawing pulverized concrete using a rotary-percussion hammer (preferably electric), or by taking cores and then pulverizing the concrete in the laboratory. Field pulverization samples are generally taken at various locations of the suspect member under investigation.

At each level of sampling, the pulverized material is collected and stored in a clean container, the hole is vacuum cleaned, and the next sample is drawn at the next desired depth. Where deep holes are to be drilled, care must be taken to prevent contamination of the

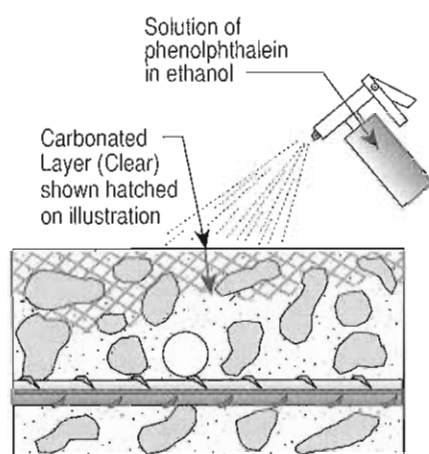
sample from the abrasion of the rotary drill bit against the side of the hole. Using a drill bit with a stepped-down bit diameter will reduce the chance of contamination. Powdered samples are analyzed using a wet chemical method.¹

Separating cast-in chlorides from chlorides that have entered the structure from the surface can be done by comparing the chloride content at various levels in the suspect member. Cast-in chlorides will generally have similar chloride contents throughout the member, whereas chlorides that have entered the concrete after casting will have higher concentrations at the surface and lower levels further into the member.



¹NCHRP Report 118, Detecting Defects and Deterioration in Highway Structures, TRB, 1985, p. 17.

Section 6: Depth of Carbonation

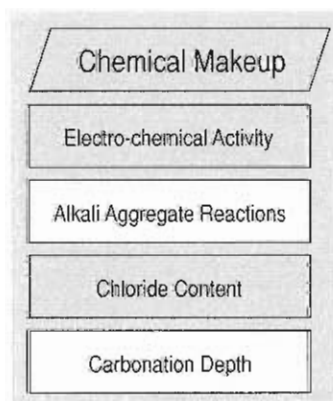
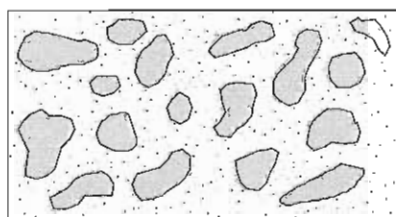


Surfaces with pH below 10 (carbonated) will have no change in color, with a pH above 10 the color of concrete will change to a pink color.

Carbonation of concrete is the reaction among acidic gases from the air, moisture, and the alkaline cement paste. To determine the depth of carbonation, a fresh concrete surface must be exposed. This can be done by core sampling the suspect surface and splitting the core with a hammer and chisel. The position of the carbonation front is measured by spraying the concrete surface with an acid-based indicator which changes the colors at a pH of about 10, indicating the inter-

face between carbonated and uncarbonated zones. The most commonly used indicator for this purpose is a solution of phenolphthalein, which colors the concrete an intense red (pink) at pH values greater than 10 and is colorless at pH values less than 10. The pH-indicators are not supposed to give the exact pH value of the concrete, but merely to measure the depth of the layer altered by carbonation.

Section 7: Petrographic Analysis



Petrographic analysis is a detailed examination of concrete to determine the formation and composition of the concrete and to classify its type, condition, and serviceability. The petrographic examination attempts to answer two general, objective questions: "What is the composition?" and "How is it put together?"¹ The petrographic examination helps to improve the extrapolation from test results to performance in situ. Together with various other concrete tests, petrographic analysis helps to determine why this concrete in situ behaved in the way it did, and how it may behave in the future. To perform this type of analysis, concrete specimens are taken

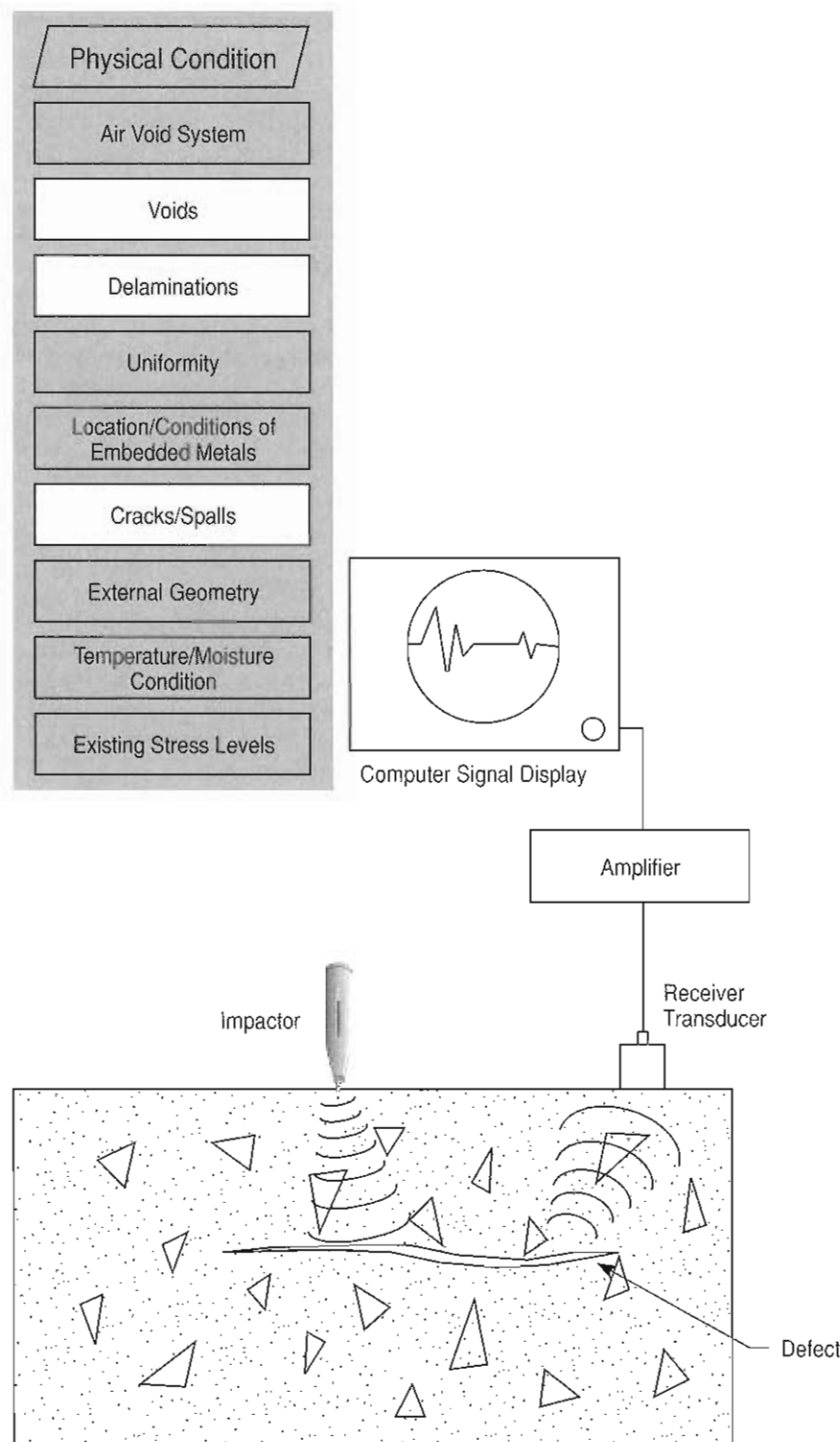
from the structure and are prepared by either polishing or etching a surface of the specimen. Petrographic examination includes identification of mineral aggregates, aggregate-paste interface, assessment of the structure, and integrity of the cement paste. Petrographic examination helps determine some of the following mechanisms:

1. Freeze-thaw resistance
2. Sulfate attack
3. Alkali-aggregate reactivity
4. Aggregate durability
5. Carbonation

Petrographic examination is a highly specialized practice requiring skilled petrographers.

¹Mather, Katherine, *Petrographic Examination*, ASTM STP 169-A, Concrete and Concrete-Making Materials, Philadelphia.

Section 8: Locating Voids, Cracks, and Honeycomb



Impact Echo Method

Detecting flaws under the surface of concrete has always been difficult. Recent developments in instrumentation and computer technology can provide a reliable method of locating voids, cracks, honeycomb, and other flaws. The impact-echo technique works by impacting the concrete surface with a short duration stress pulse that is reflected from defects and external boundaries back to a receiver (transducer). The signals received are converted into a frequency spectrum and are displayed on a computer screen. Artificial intelligence software is used to analyze these signals, predicting the probability and depth of defects. The system works quickly, taking approximately two seconds to process each reading.¹

¹Materials Journal of the American Concrete Institute, Sept.-Oct. 1991, "Detecting Flaws in Concrete Beams and Columns Using the Impact Echo Method," by Yiching Lin and Mary Sansalone.

Section 9: Locating Voids, Cracks, and Honeycomb

Physical Condition
Air Void System
Voids
Delaminations
Uniformity
Location/Condition of Embedded Metals
Cracks/Spalls
External Geometry
Temperature/Moisture Condition
Existing Stress Levels

Ultrasonic Pulse Velocity Methods

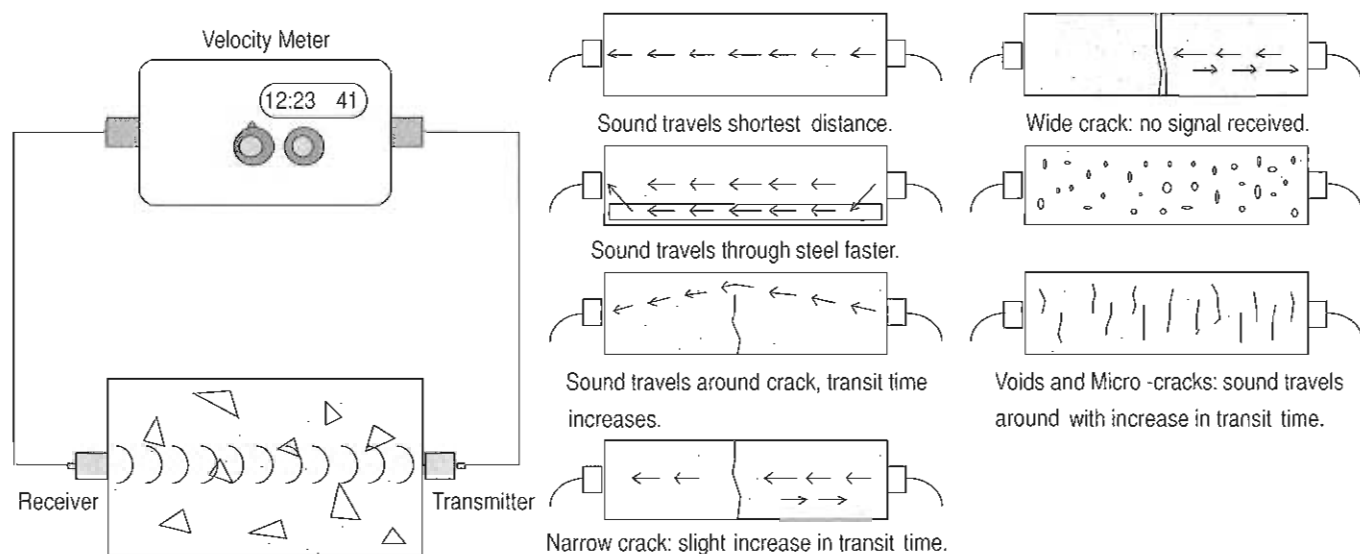
Pulse velocity is the measurement of the transit time of an ultrasonic pulse between a transmitter and a receiver. If the distance between the transmitter and the receiver is known, the velocity of the pulse can be determined (distance divided by time). In general, the more dense and strong (compressive) the concrete being tested, the higher the velocity of the pulse.

To test concrete, contact between the concrete and the transmitter and receiver is made with a coupling agent such as a petroleum jelly. The velocity of sound waves through the concrete is reduced by the presence of voids or cracks.

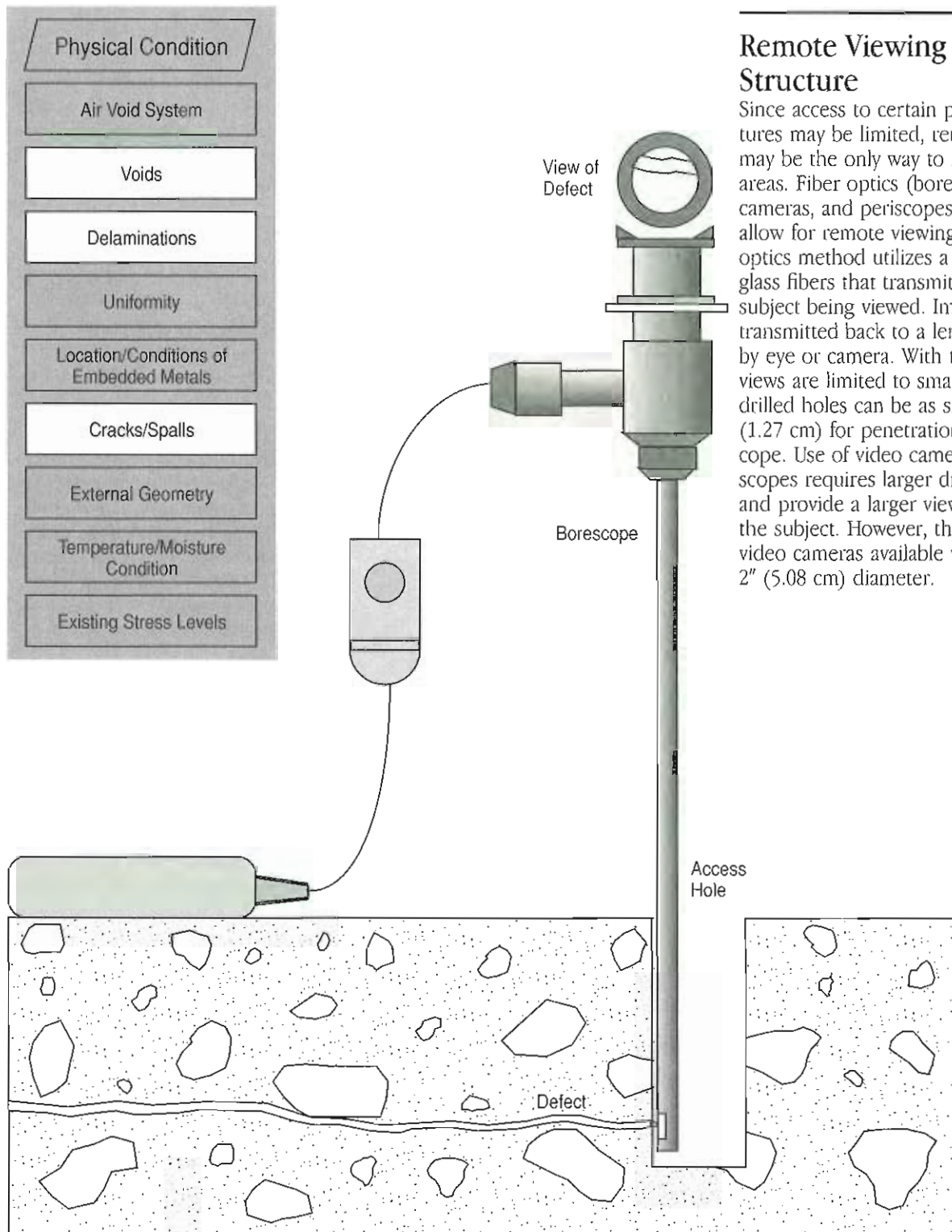
Transit velocity is also influenced by the presence of reinforcing steel. If the reinforcing steel runs parallel to the wave propagation, the influence of the steel will be high, thus reducing the transit time. Transit velocity for reinforcing steel will be 1.2X to 1.9X, as compared to concrete. There is a correlation between pulse velocity and compressive strength, generally ± 20 percent.

The pulse velocity method is an excellent tool rapidly to compare concrete uniformity from one part of the structure to another. Another valuable use of this technique is the non-destructive evaluation of cracks that have been filled with epoxy (epoxy injection). In this case, the transmitter and receiver are fixed at a given distance apart, and the assembly is placed perpendicular to the crack, where pulse velocity measurements are taken. Calibration is carried out in an uncracked section of the concrete. Readings taken along the repaired crack are compared to the calibration reading of the uncracked section (fully monolithic). A properly repaired crack (one that is completely filled with cured epoxy resin) will display a transit velocity equal to that of the uncracked section. The values of this method of quality assurance are speed and the number of tests that can be performed.¹

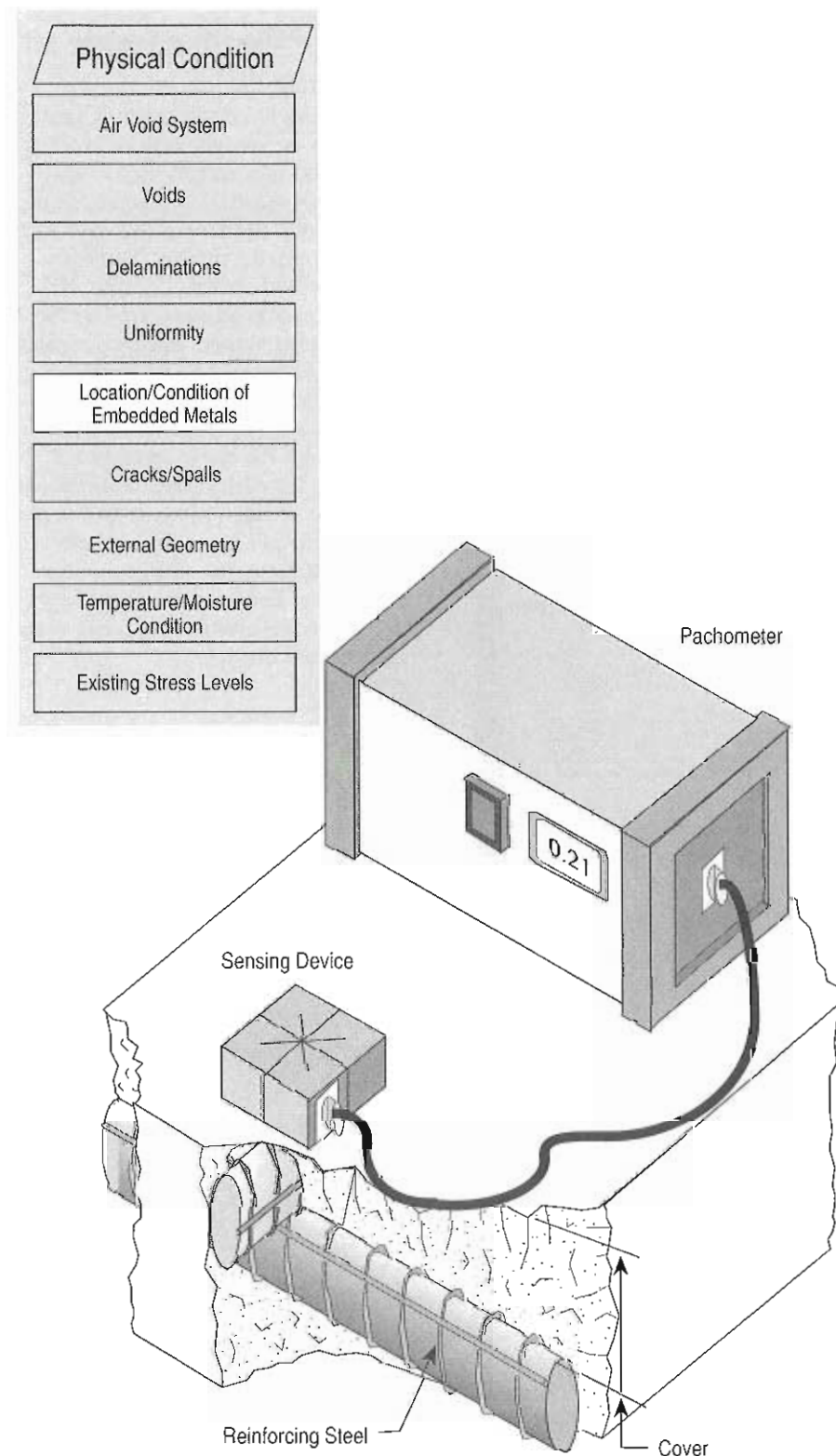
¹NCHRP Report 118, Detecting Defects and Deterioration in Highway Structures, TRB, 1985, p. 13.



Section 10: Locating Voids, Cracks, and Honeycomb



Section 11: Locating Embedded Reinforcing Steel



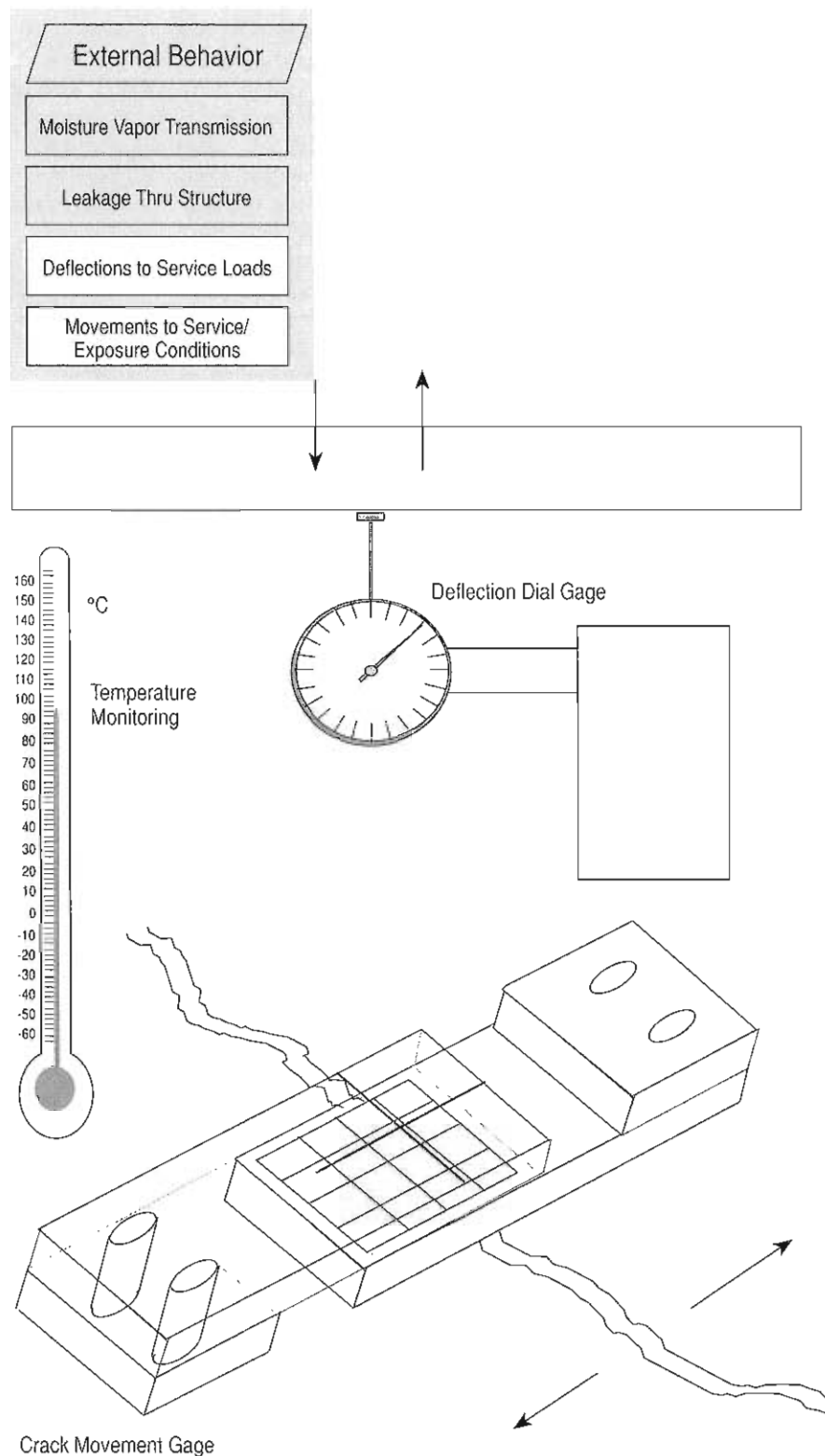
Magnetic devices, known as *pachometers* or *covermeters*, are used to determine the location of embedded steel reinforcement in concrete. If the size of reinforcement is known, the amount of concrete cover can be determined. In general, these devices can measure cover to within 1/4" (6 mm) at 0 to 3" (0 to 75 mm) from the surface. The accuracy of the devices is dependent on the amount of reinforcing steel that is present in concrete. The more congested the reinforcing, including multiple layers, the less accurate the device becomes. In some cases, when other bars interfere, the device cannot identify either location or depth of cover.

Calibration of the pachometer is recommended in cases where there is possible magnetic interference from metallic particles or additives, such as fly ash, in the concrete. Calibration can be done by excavating the concrete, measuring the actual cover, and adjusting the pachometer to the actual measurement.

Pachometers are also reliable in locating post-tension strands when the strands are 0 to 3" (0 to 75 mm) from the surface.

Other devices, such as ground-penetrating radar or x-ray, can be used for locating embedded metals when the pachometer fails to provide the necessary information. Ground-penetrating radar can be used for locating reinforcing steel bars or other non-magnetic metals; however, x-ray is the most accurate method. An x-ray works by photographing the inside of the concrete in question, showing all embedded objects (similar to a chest x-ray). X-ray exposure at each location will take 30 minutes or more to penetrate the concrete element. The thicker the member, the longer the exposure time.

Section 12: Monitoring Movements

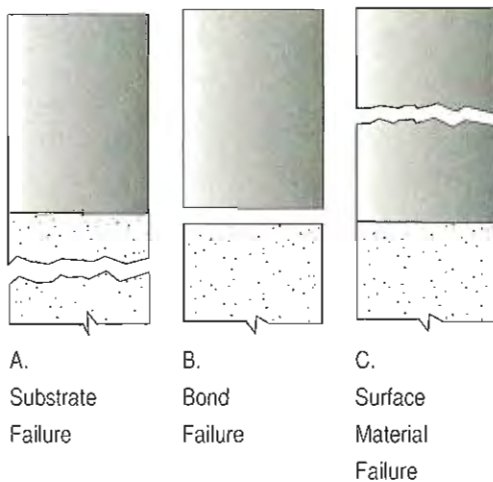


Monitoring movement in structures is important when assessing the behavior of the structure in response to changes in loads, temperature, internal conditions, and support at its foundation. The monitoring of cracks can be conducted with various tools including *optical comparitors*, *glued glass strips*, *glued-in-place crack gauges*, *LVDT's (electrical transducers)*, and *extensometers*. Changes in crack widths are generally related to temperature changes, but can also be caused by settlement, creep, and load-related strains. Expansion joint movements can be measured with hand rulers or dial gauges; however, actual deflection of members is best measured with dial gauges.

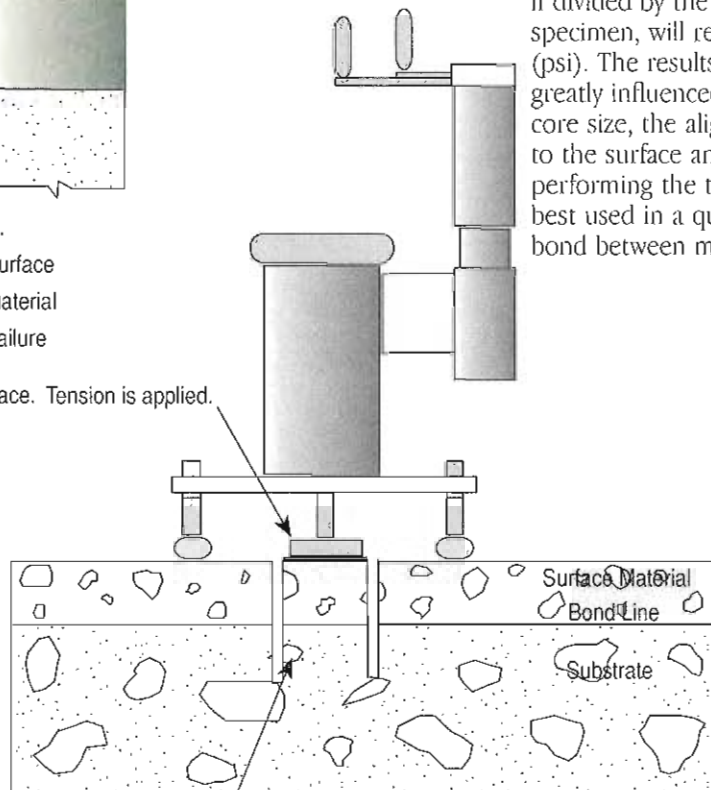
Section 13: Bond Strength of Overlays and Coatings: Pull-off Testing

Mechanical Properties
Compressive Strength
Tensile Strength
Flexural Strength
Bond Strength
Permeability/Density

Types of Tensile Breaks



Device is glued to surface. Tension is applied.



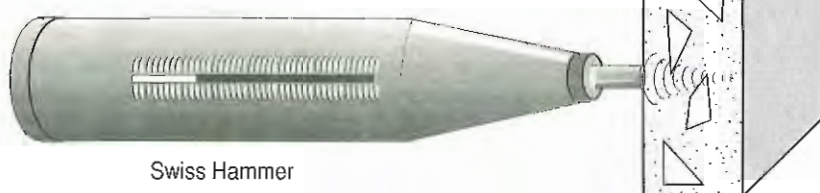
Determining the bond strength of overlays and other surface-bonded materials can be accomplished through in situ testing. One useful in situ test is the pull-off test, which measures the bond between two layers. In this test, a core is made through the surface layer into the second layer, providing an isolated test location where the pull-off tester can be attached. Once attached, the tester generates a tensile force on the core until tensile failure occurs. There are three types of possible tensile failure:

1. Failure in the substrate layer.
2. Separation at the interface between the substrate and the surface layer (bond failure).
3. Failure in the surface layer.

The testing device can also record the force required to cause failure, which, if divided by the surface area of the specimen, will result in tensile strength (psi). The results of a pull-off test are greatly influenced by aggregate size, core size, the alignment of the device to the surface and the care taken in performing the test. The results are best used in a qualitative review of the bond between materials.

Section 14: In Situ Compressive Strength: Rebound and Penetration Methods

Mechanical Properties
Compressive Strength
Tensile Strength
Flexural Strength
Bond Strength
Permeability/Density
Physical Condition
Air Void System
Voids
Delaminations
Uniformity
Location/Conditions of Embedded Metals
Cracks/Spalls
External Geometry
Temperature/Moisture Condition
Existing Stress Levels



Swiss Hammer

Rebound and penetration methods are used to measure the surface hardness of concrete. Since surface hardness is proportional to concrete compressive strength, these strengths can be predicted to within ± 25 percent. Rebound methods (Schmidt Hammer or Swiss Hammer) utilize a spring-loaded plunger that impacts the surface, causing the mechanism to rebound. The rebound is measured and compared to the initial extension of the spring, yielding a rebound number. Rebound can be affected by the angle of test, surface smoothness, type of aggregate, carbonation of concrete, and the moisture content. When evaluating concrete, the rebound method is best used only to measure the general uniformity of concrete and to identify questionable areas that may require further study.

Penetration methods¹ are similar to rebound methods, but use more powerful energy to drive a probe into the concrete surface. The Windsor Probe, the most common type of penetration method, drives a hardened alloy probe 1/4 in. (6mm) in diameter into the concrete, using a powder charge. The exposed length of the probe is measured and is used to determine the compressive strength. The accuracy of determining compressive strength is subject to many variables, such as aggregate type. Calibration of the Windsor Probe is best done by obtaining and testing a concrete core from a structure being investigated.

¹NCHRP Report #118, and ASTM C 803.

Additional Sources of Information

Evaluation and Repair of Concrete Structures, Engineer Manual, EM1110-2-2002, U.S. Army Corps of Engineers, 1986.

Condition Surveys of Concrete Bridge Components—User's Manual, NCHRP Report No. 312, TRB, Washington, D.C., 1985.

Detecting Defects and Deterioration in Highway Structures, NCHRP 118, 1985.

ASTM C 823—Standard Practice for Examination and Sampling of Hardened Concrete in Constructions.

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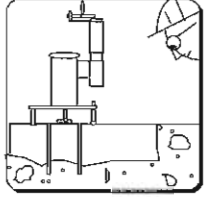
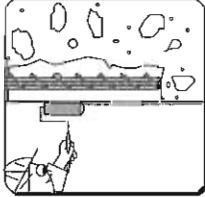
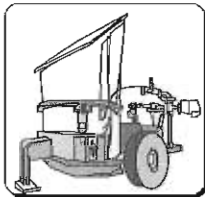
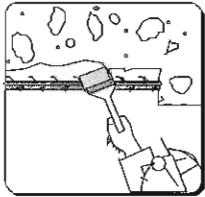
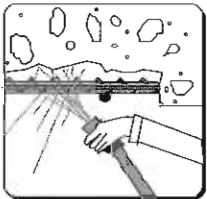
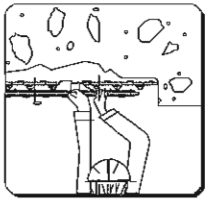
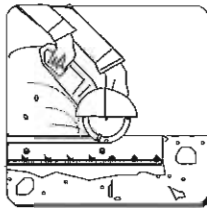
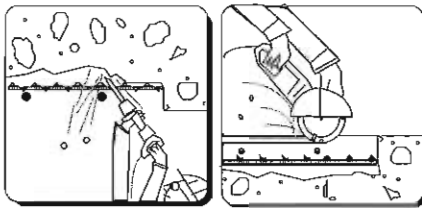
Part Three **Surface Repair**

Part Three

Surface Repair

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Introduction to Part Three

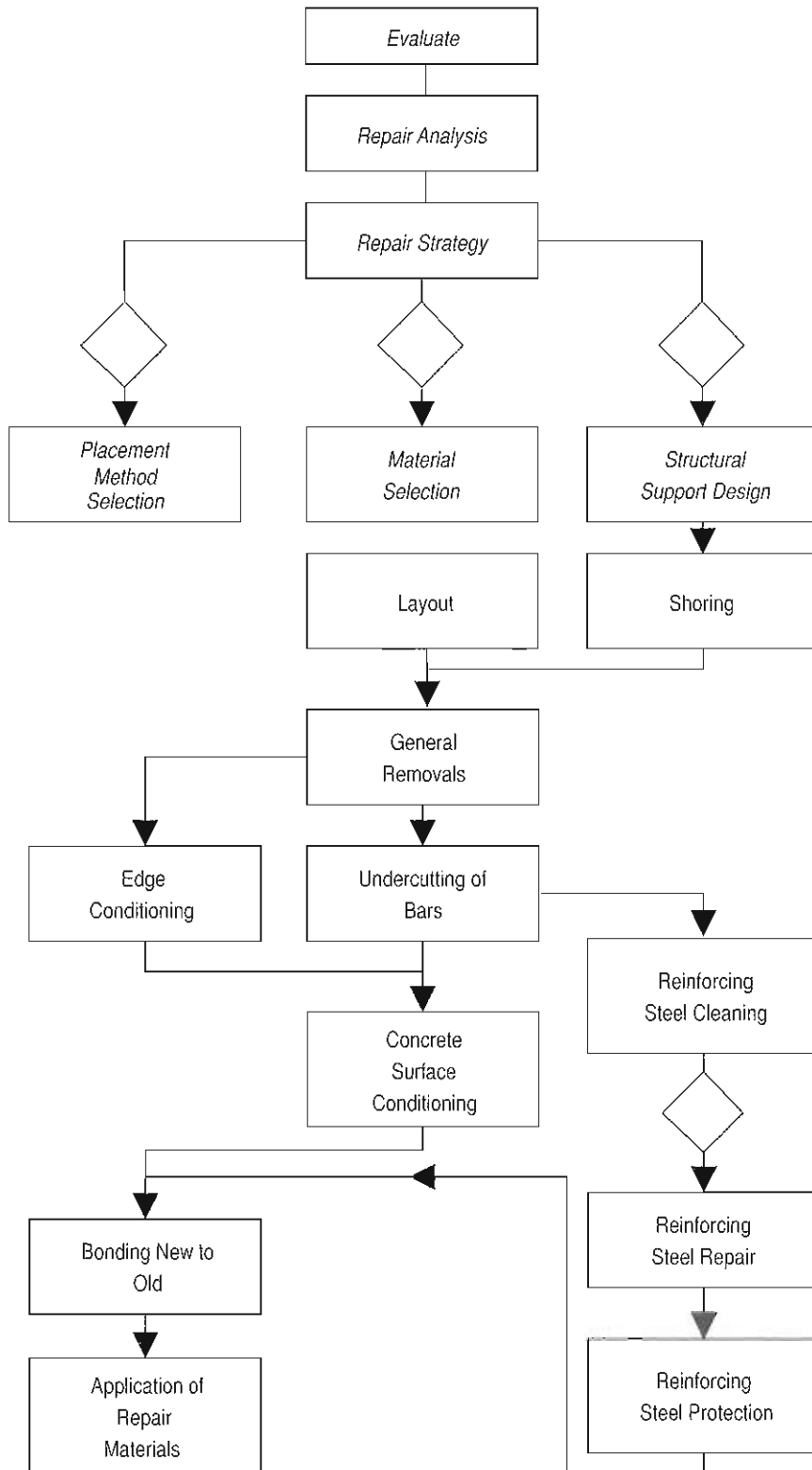
Surface repair of concrete has been practiced ever since the first concrete placement. Much has been learned and forgotten over this period. The process was once simple, with few choices for materials and placement techniques. The current practice of surface repair is far more complex than in the past for a number of reasons as indicated below.

- High performance concrete is used for new construction, (high strength, lightweight, containing different additives).
- Design practice is more precise.
- Concrete is used for many applications involving aggressive environments.
- Atmospheric pollution and the use of de-icing salts are more prevalent.
- Structures are more complex; including post-tensioned, precast, and composite.
- A wide variety of repair materials is available for special applications.
- More placement techniques are available for repair.

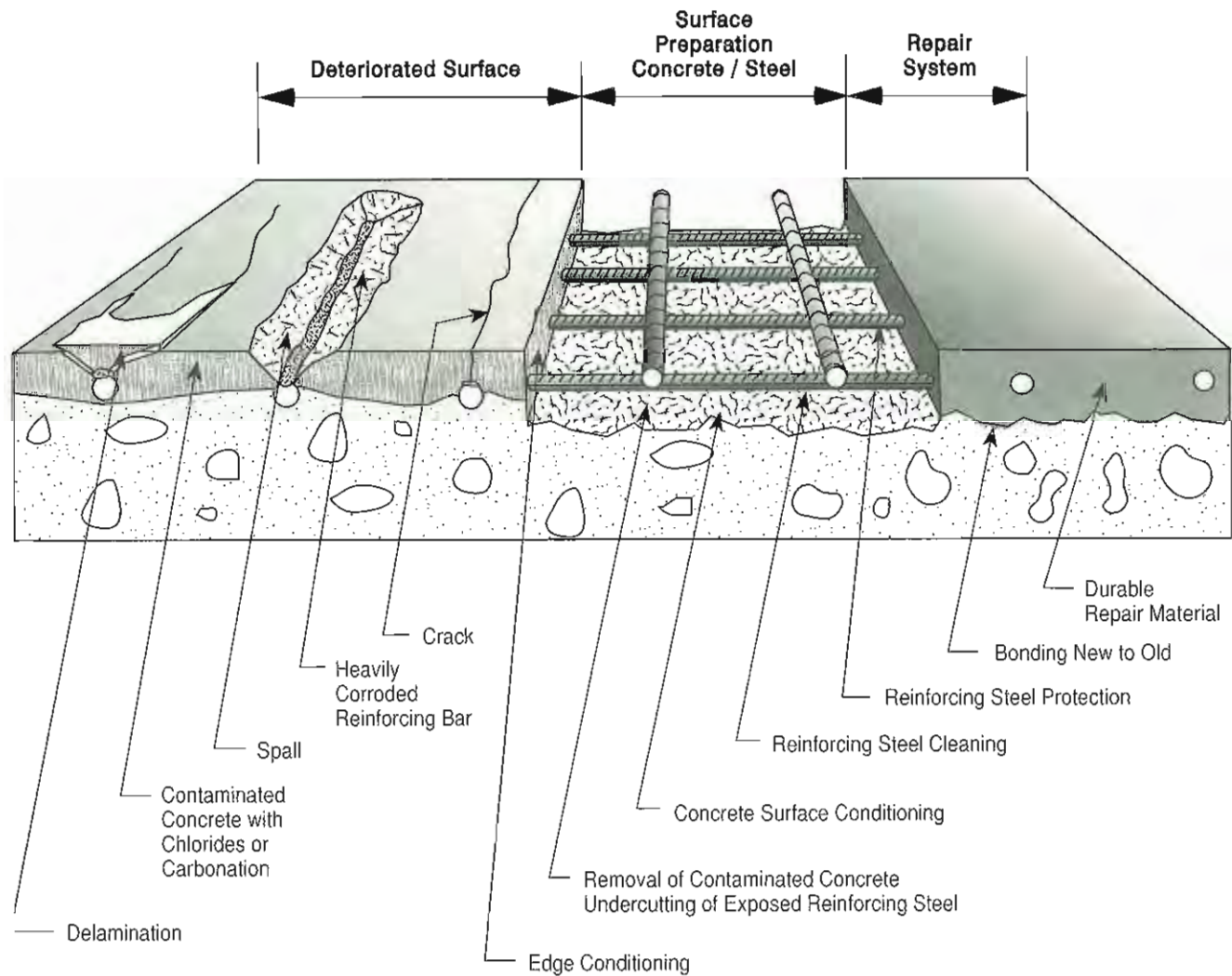
The current state of the art techniques for surface repair requires a working knowledge of material testing and evaluation, structural engineering, surface preparation tools and effects, material properties and behavior, environmental regulations and placement technology. Accomplishing durable, effective repairs is not a sure process. Much can go wrong, there are few redundancies, and many steps depend upon the success of others. Building durable and effective surface repairs is an ever-improving process. The following flow chart details these major steps involved in surface repair:

- Repair analysis, strategy and design
- Material selection
- Surface preparation
- Reinforcing steel cleaning, repair and protection
- Bonding surface repairs to existing substrate
- Placement techniques

Flow Chart of General Procedures



Anatomy of Surface Repairs



Section 1: Analysis, Strategy & Design

The following topics are covered in this section:

Introduction to Analysis, Strategy & Design

Structural Needs

Types of Stress Acting on Repairs

Performance Requirements, Examples

The Challenge of Placing Loads into Repairs

Cause/Effect Design Error

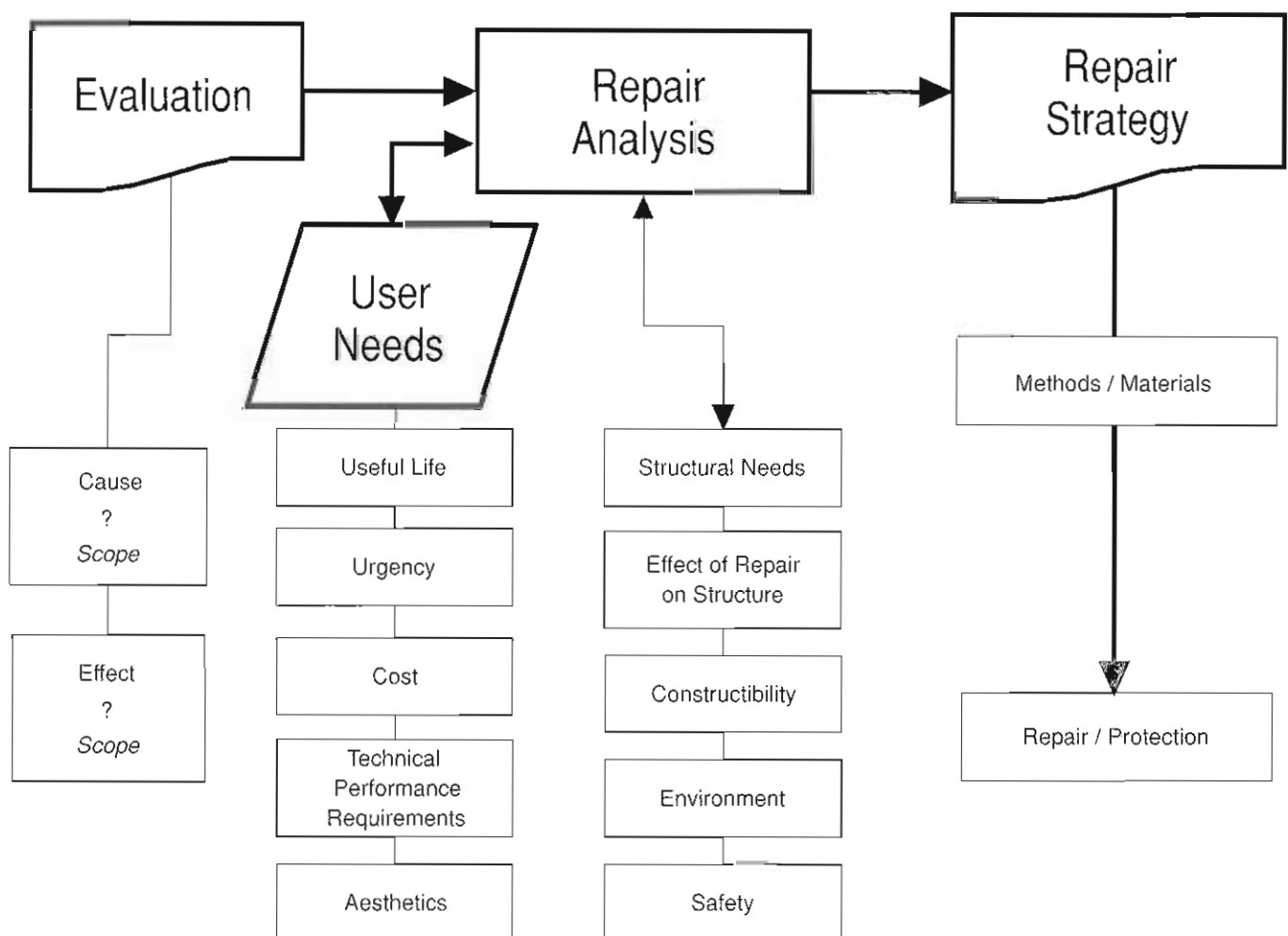
Repair Problem—Analysis and Strategy

Introduction to Analysis, Strategy & Design

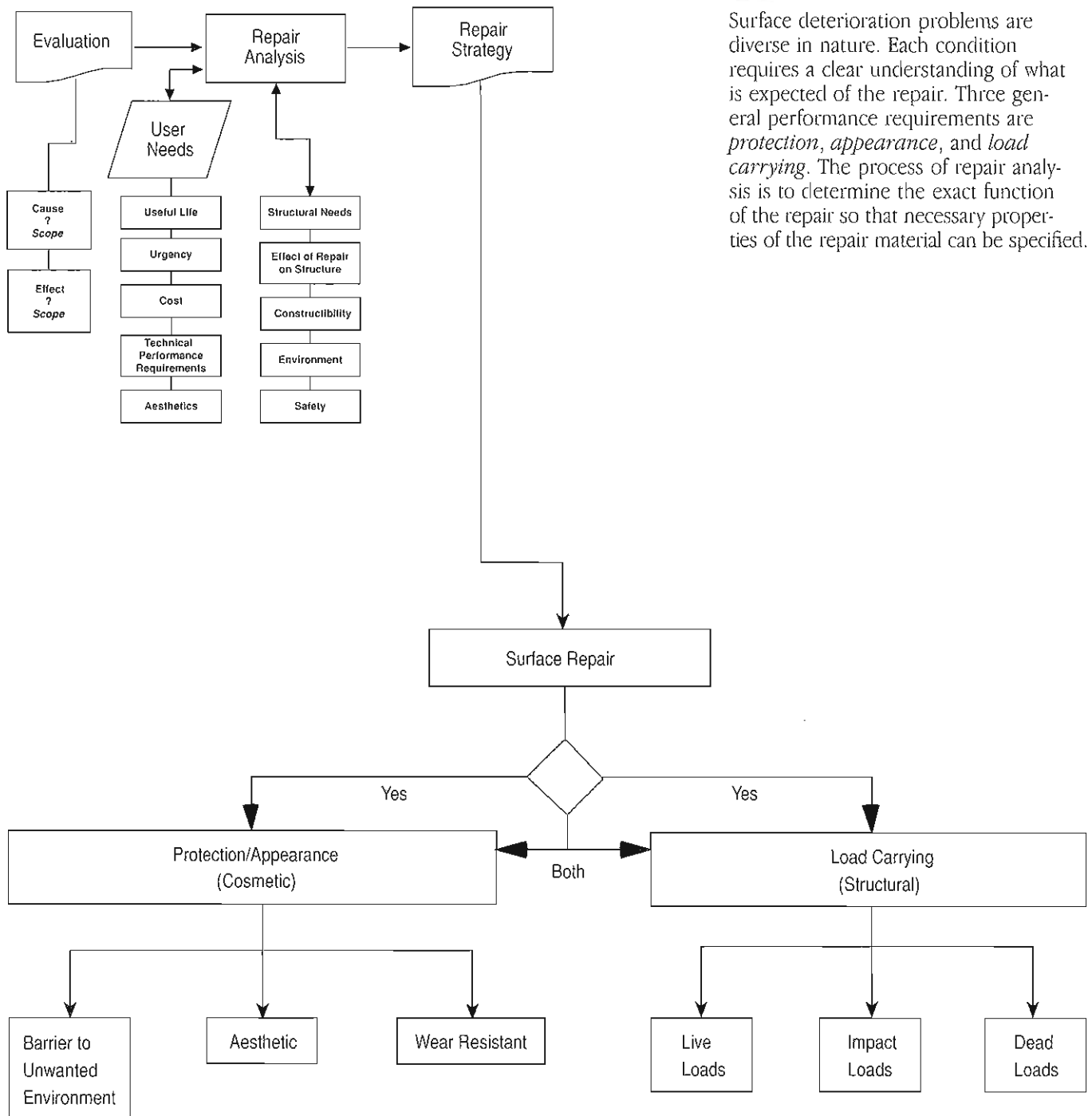
The process of solving concrete repair problems includes repair analysis, strategy and design. A comprehensive evaluation must be conducted, including the scope of both the cause and effect of the deterioration. The results of the evaluation, together with the user's needs or requirements, form the necessary external information to begin the design process. The final design presents a solution based on considerations of durability, constructibility and compatibility with the existing structure.

The section, "Surface Repair Analysis, Strategy and Design," covers the cause/effect relationship in repair design, performance criteria for repair methods and material selection, the structure's impact on repair effectiveness, and some typical repair design errors.

It is important to note that the scope of this book precludes a detailed examination of this enormous topic; the discussion offered here is intended to provide the reader with a broad framework to perform the design of a repair project.

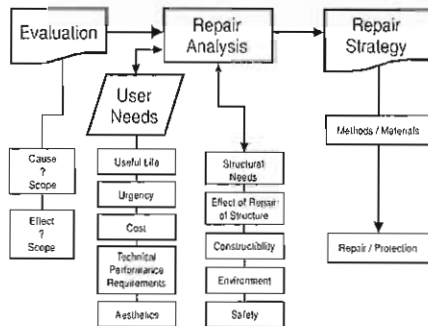


Performance Requirements



Surface deterioration problems are diverse in nature. Each condition requires a clear understanding of what is expected of the repair. Three general performance requirements are *protection, appearance, and load carrying*. The process of repair analysis is to determine the exact function of the repair so that necessary properties of the repair material can be specified.

Structural Needs



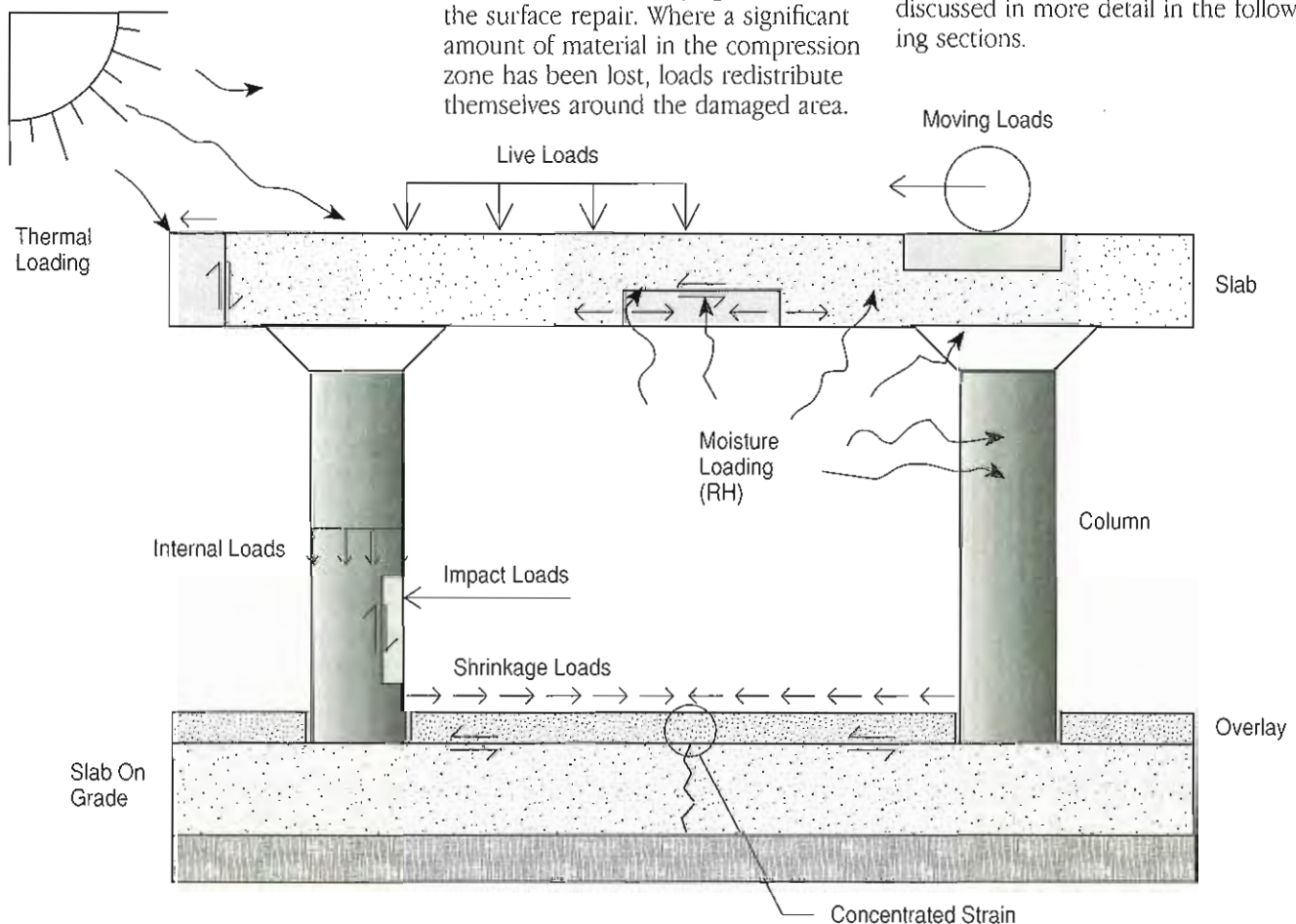
A concrete surface repair must replace damaged concrete, restore required structural function, protect itself and possibly underlying concrete from aggressive environments, and restore any lost user performance requirements.

It is important to analyze all possible stresses in the repair material and at the interface between the repair and the existing substrate. Stresses in the repair are generated by relative volume changes between the repair and the existing concrete substrate, and by service loads carried by the repair. Stresses in the repair must be within the capacity of the new and existing materials. Otherwise, failure may occur.

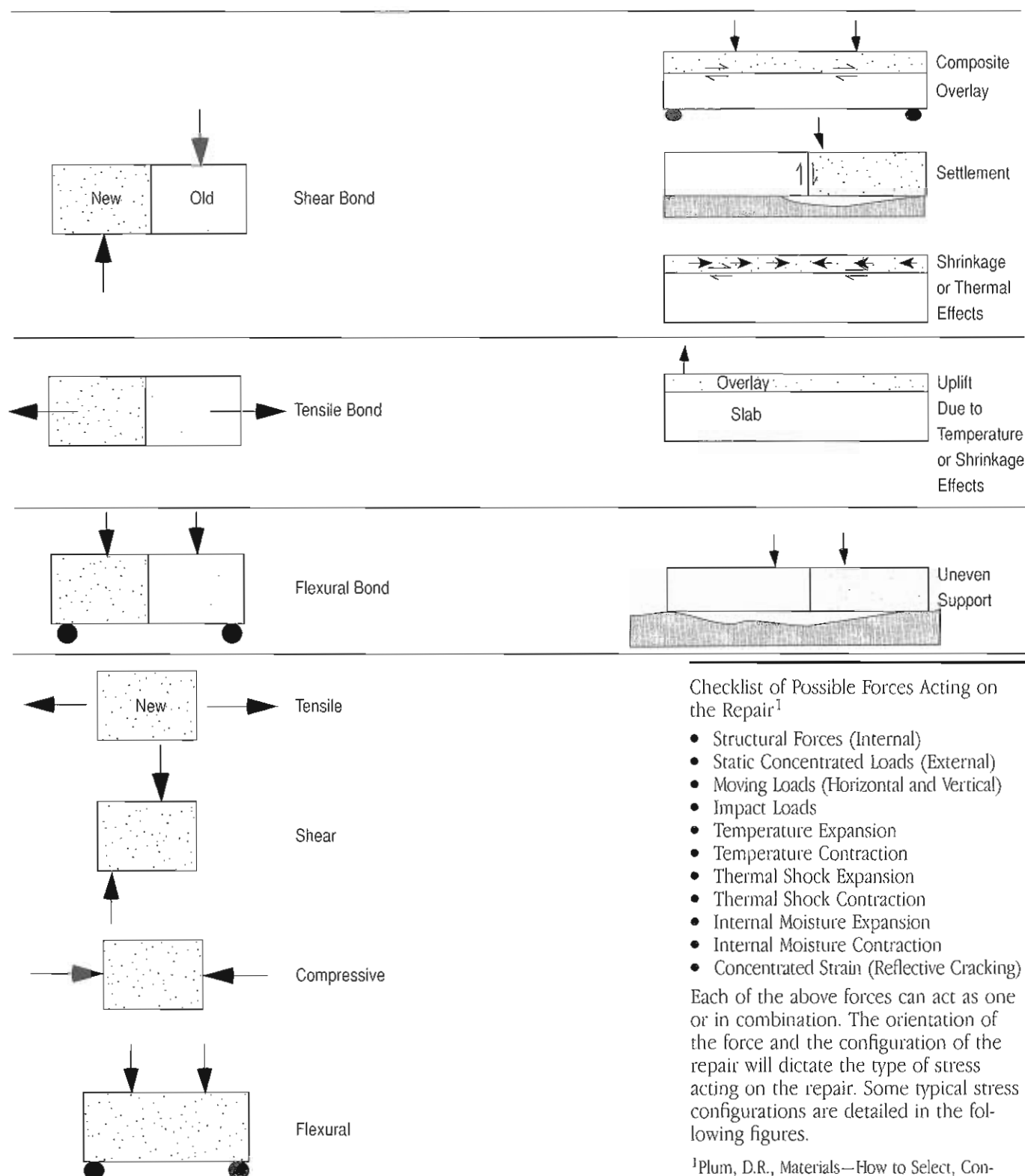
In many situations it is difficult to achieve the stress-carrying function of the surface repair. Where a significant amount of material in the compression zone has been lost, loads redistribute themselves around the damaged area.

To recreate the original load distribution, full load relief must be provided during the surface repair process. Repair material must be installed, cured, and after the material reaches the specified strength, loads would be allowed on the member. Load relief from members is typically provided with temporary shoring and jacking.

Relative volume changes caused by drying shrinkage of the new material place the repair into tension (assuming the repair material is restrained from shrinkage by the bond between the repair material and the existing concrete). In most applications, the desirable condition is to have the repair in a compressive state so that compressive loads can be carried. This topic is discussed in more detail in the following sections.

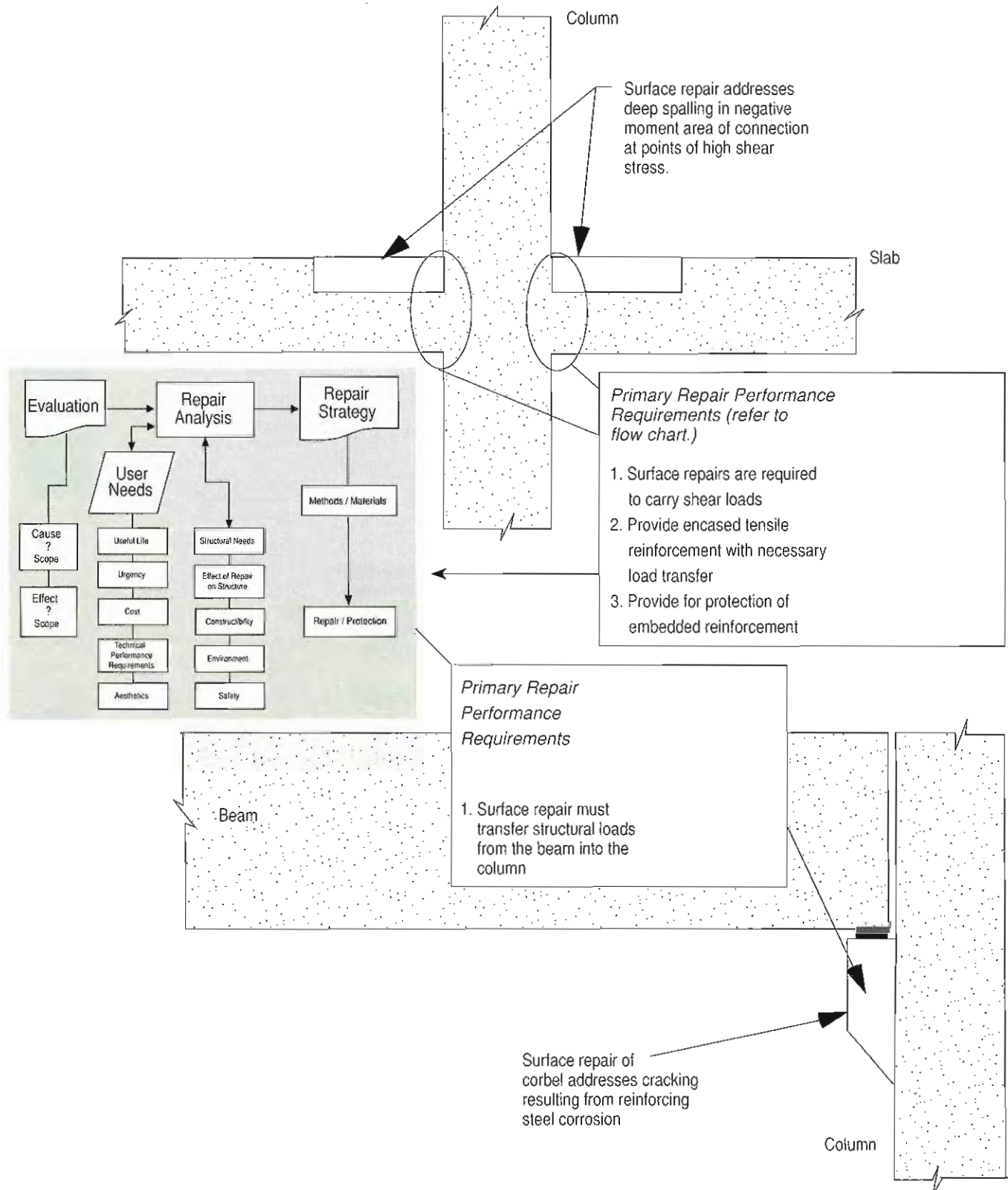


Types of Stress Acting on Repairs



¹Plum, D.R., Materials—How to Select, Construction Maintenance and Repair, November/December 1991, England, pp. 27–30.

Performance Requirements Examples

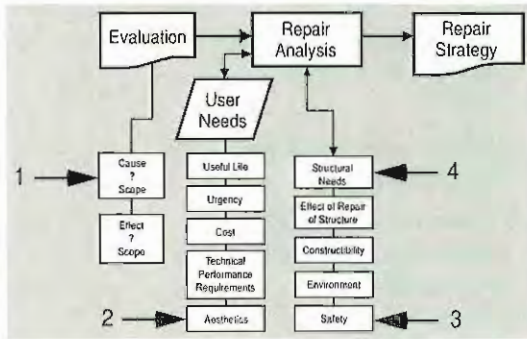


Performance Requirements Examples, continued

Repair Performance Requirements

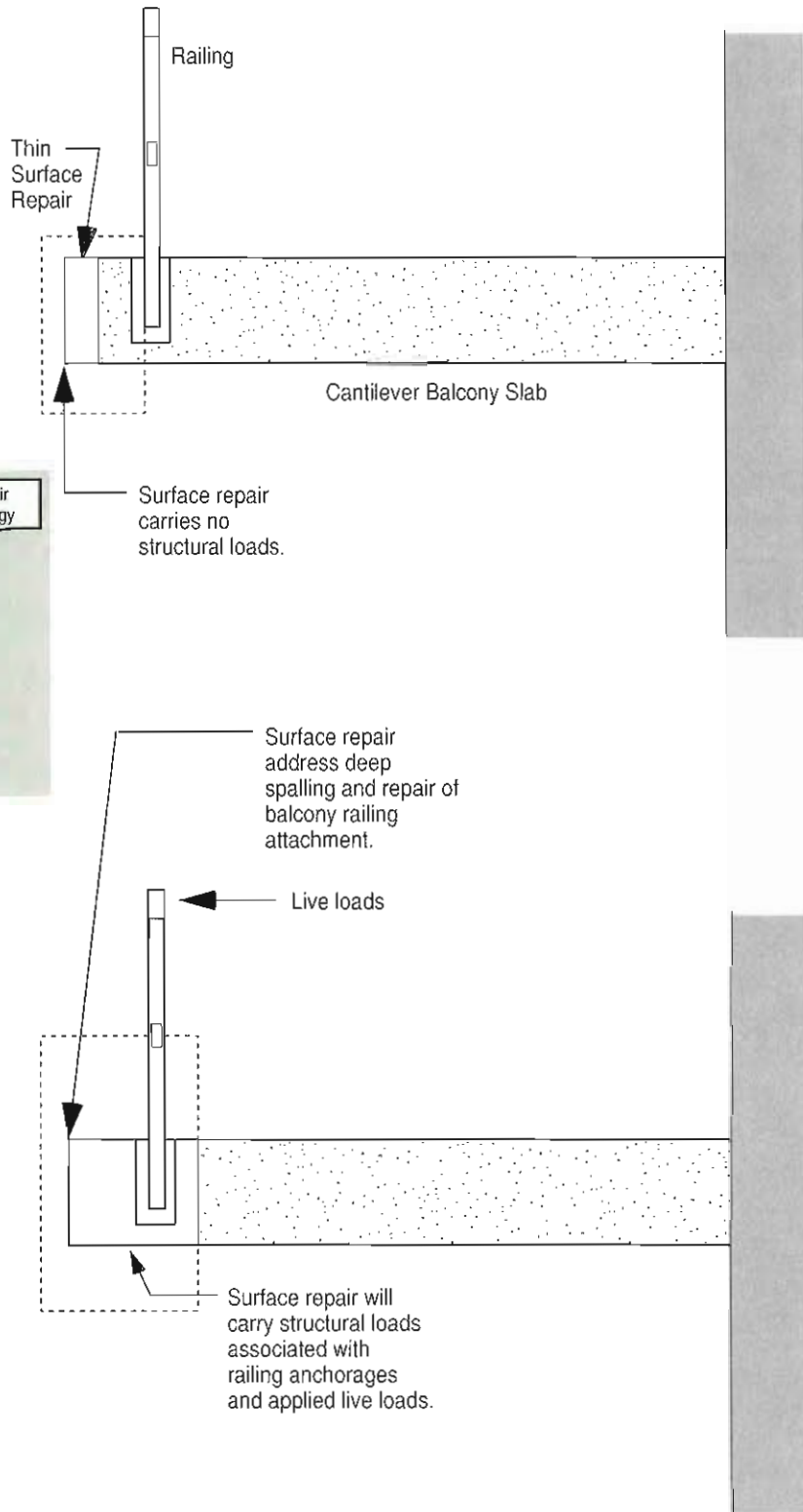
1. Provide for protection of embedded reinforcement.
2. Aesthetically pleasing.
3. Will not come loose from substrate.

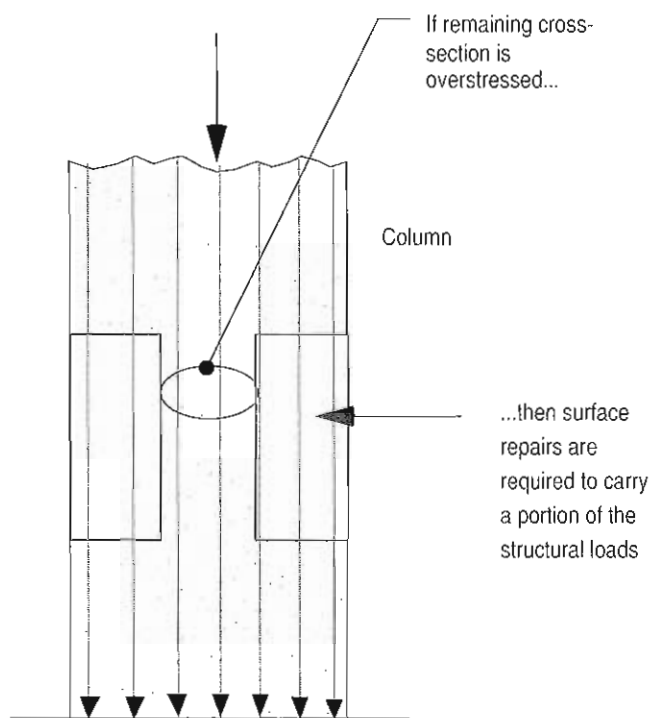
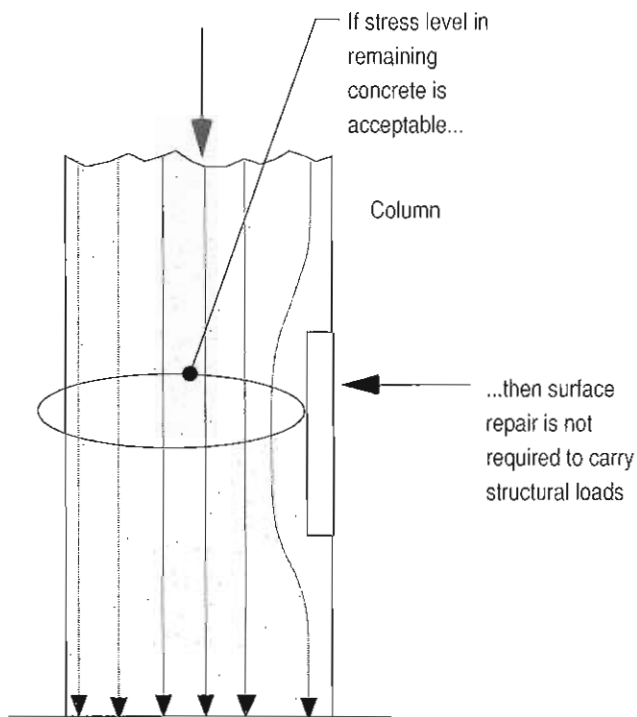
(See flow chart for number reference.)



Repair Performance Requirements (See flow chart for number reference)

1. Provide for protection of embedded reinforcement.
2. Aesthetically pleasing.
3. Will not come loose from substrate.
4. Will carry structural loads from railing system.

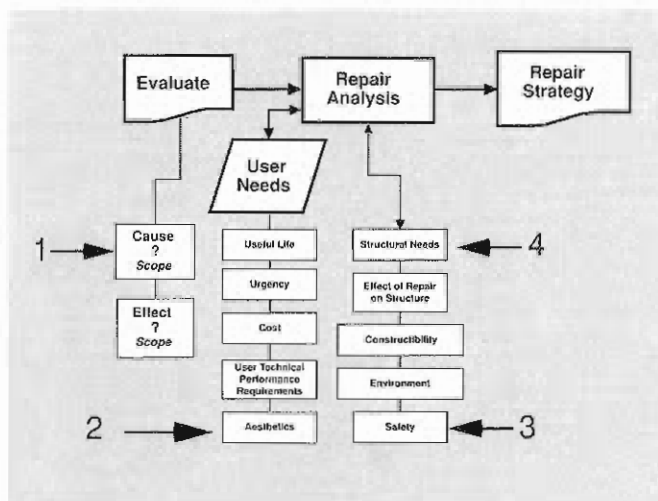




Primary Repair Performance Requirements

1. Provides for protection of embedded reinforcement.
2. Aesthetically pleasing.
3. Will not come loose from substrate.

Refer to flow chart for number references.

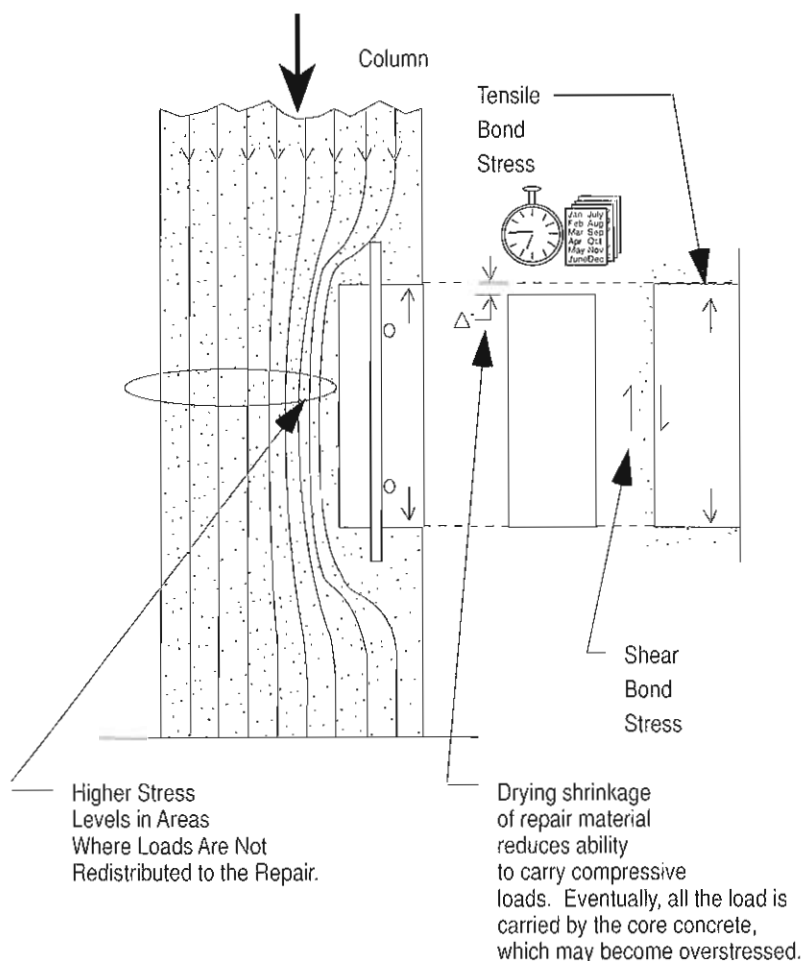
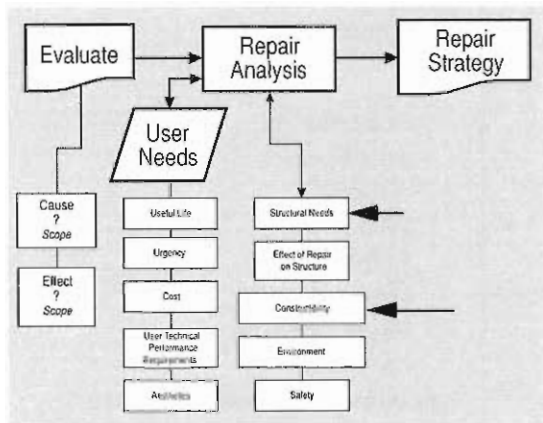


Primary Repair Performance Requirements

1. Provides for protection of embedded reinforcement.
2. Aesthetically pleasing.
3. Will not come loose from substrate.
4. Will carry a portion of compressive loads.

Refer to flow chart for number references.

The Challenge of Placing Loads into Repairs



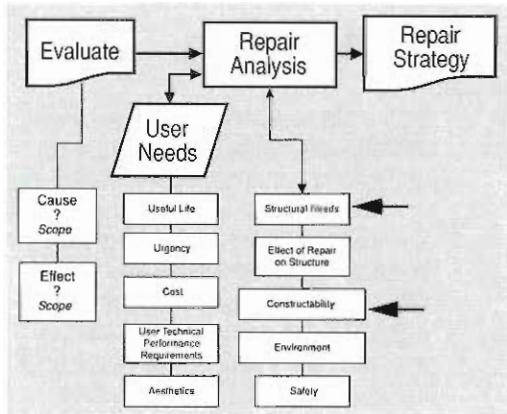
Column Repair

Columns carry compressive loads. After surface deterioration, compressive loads within the column are redistributed around the affected area, increasing the stress level in the remaining cross-section. A surface repair will not carry its share of stress unless the compressive loads are removed from the column during repair operations. Another factor that affects the ability of the repair to carry the expected proportion of the load, is drying shrinkage of the repair material. Drying shrinkage reduces the volume of repair material relative to the existing concrete, and as a result, the surface repair is not filling the originally prepared space. Excessive drying shrinkage is evident when tension cracking appears on the surface of the repair. This topic is discussed in more detail in the section, "Surface Repair Material Requirements."

Procedure for placing loads in repair materials

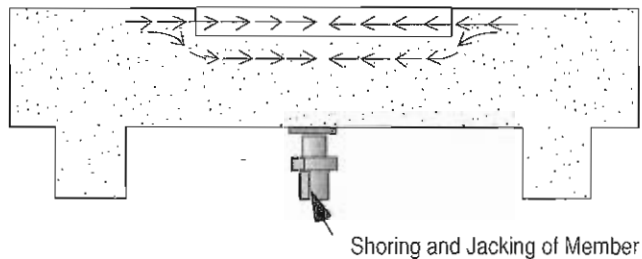
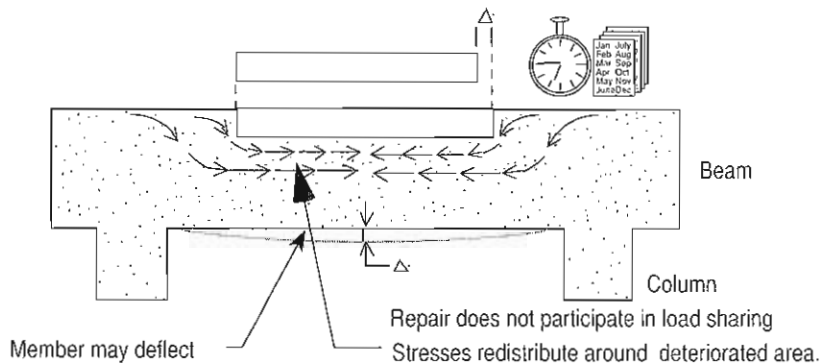
1. Remove loads from member by appropriate shoring and jacking during repair procedure and maturity of repair materials.
2. Select extremely low drying shrinkage repair materials (See note).
3. Select repair materials with low creep values over anticipated environmental conditions.
4. Select repair materials with a compatible stress-strain (E) relationship to the existing concrete.

Note: If the repair material has drying shrinkage of 500 microstrains, it will take an additional compressive strain of 500 microstrains in the member to begin the process of making the repair load carrying.

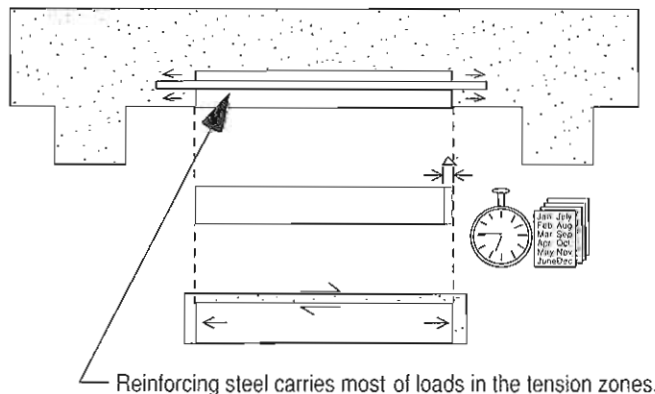


Stress Distribution in Flexural Members Compression Zone

Deterioration in compression zones of flexural members results in redistribution of stress to the remaining sound concrete section. Significant section loss may result in overstress and excessive deflection. Removal of loads during repair operations allows the repair to carry the expected proportion of the load.



Load relief during repair operation may enable the repair material to carry its share of stress.



Stress Distribution in Flexural Member's Tension Zone

Deterioration in tension zones of flexural members exposes tensile steel reinforcement. Most, if not all, tension is carried by the reinforcing steel. Loads do not usually redistribute around the deteriorated area unless the tension steel has lost cross-section in the corrosion process. If the steel has lost section, excessive deflections may result. During the repair process, relief of tension loads is desirable and is usually accomplished by temporary support of the affected member. Active shoring (shoring that carries the acting dead and live loads of the member) will allow for repair of damaged reinforcing bars at a low stress level. After completion of repairs and removal of shoring, the repaired bars will be able to carry the original loads.

Cause/Effect Design Error

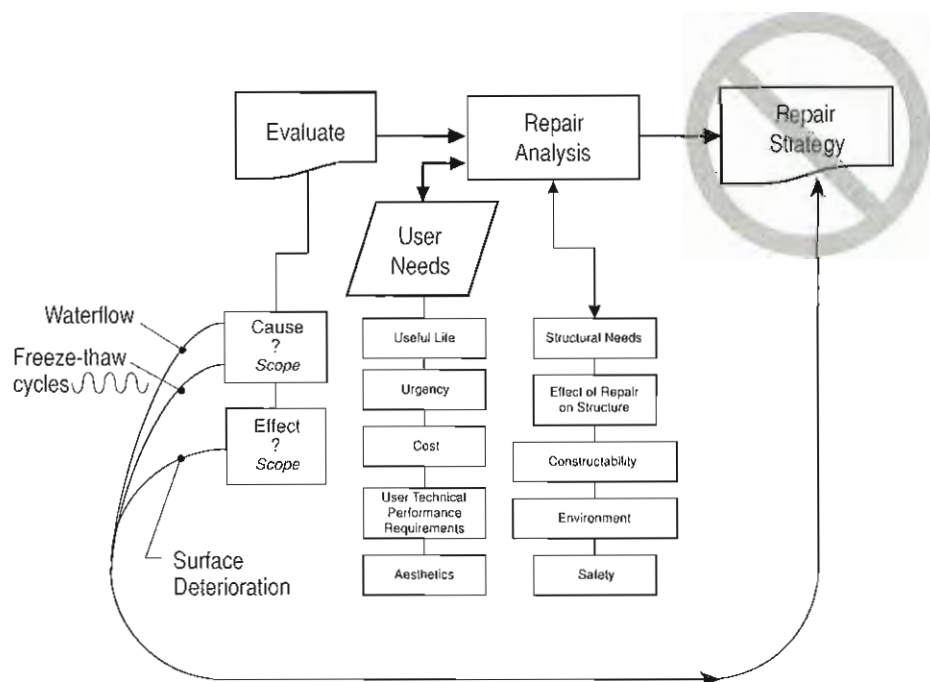
Repair of Surface Freeze-Thaw Deterioration Without Removing the Cause

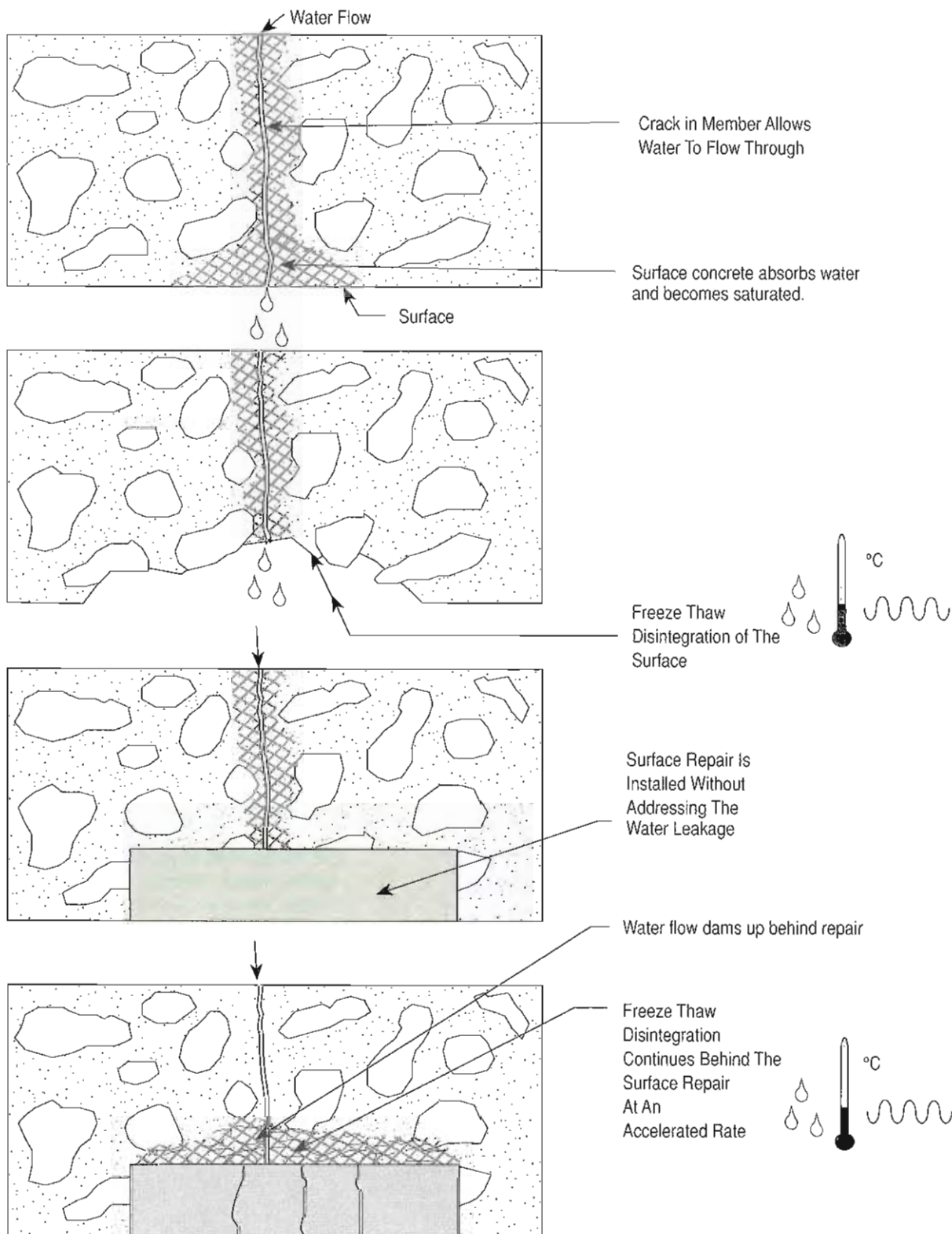
Freeze-thaw damage to concrete surfaces is common. The effect is surface disintegration; the cause is water saturation of the porous concrete matrix and freeze-thaw cycles.

A common problem found with repair of freeze-thaw damaged concrete where the source of moisture is from within the member, is continued disintegration behind the surface repair. Internal sources of moisture are typically found in structures such as retaining walls, downstream faces of dams, lock walls, and water retaining tanks. Water under a pressure head will attempt to follow a path to a lower pressure head. Paths are found through cracks, construction joints, expansion joints, and in some cases, porous concrete. Concrete adjacent to a water path may become saturated

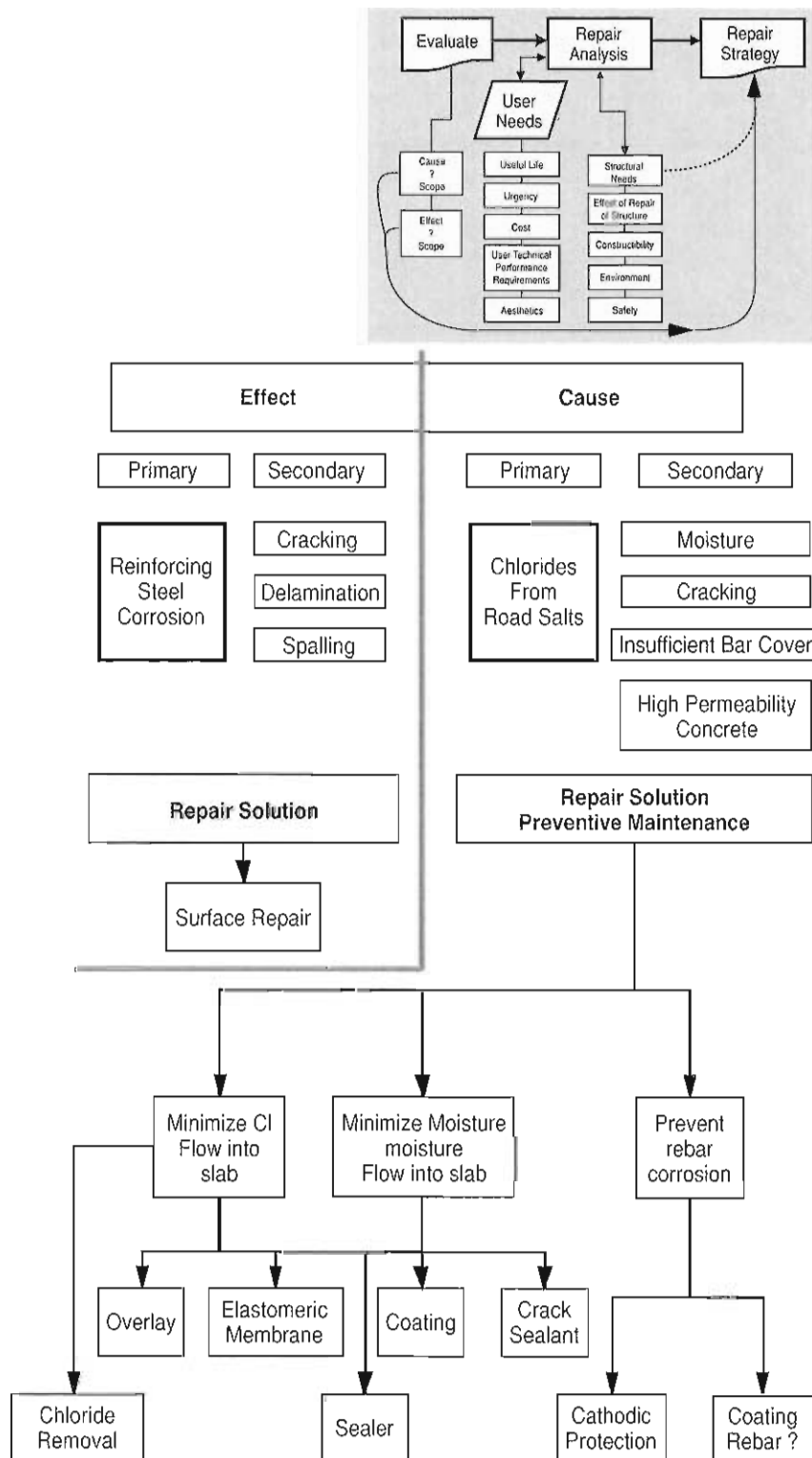
with water and, upon freezing, may disintegrate. Surface repairs that do not stop the internal flow of water into concrete are susceptible to freeze-thaw damage and may have a short life because of the continued freeze-thaw disintegration behind the surface repair. In some cases the disintegration process is accelerated because of the damming effect of the surface repair on the free flow of water moving through the structure.

When this condition exists, internal water flow should be cut off via grouting, external waterproofing techniques or drainage systems that route the flow of water through the structure. Other techniques utilize deep surface repairs, that place the bond line below the frost line.





Repair Problem



Analysis

Example: A parking structure has spalling at the traffic surface of a cast-in-place flat slab. It is decided that an in-depth evaluation of the slab should be performed to assess both the problem (effect) and the cause. The cause of concrete distress needs to be known so areas of the deck not yet affected can be controlled with preventive maintenance protective strategies (if owner so desires). The delaminated areas are located by chain drag; corrosion activity is evaluated by half cell and chloride ion content testing. The technical documentation, deck maintenance and use records, and results of the testing provide the information needed to determine the cause of concrete deterioration. Chloride ion content at the reinforcement level is found in excess of the level required for corrosion activity when moisture and oxygen are present. It is also found that spalling is limited to areas where reinforcing steel does not have an adequate concrete cover. Additional laboratory testing indicates that slab concrete is highly permeable and subject to progressive chloride penetration under current conditions. In this example, it is determined that the cause of concrete distress (spalling and delamination) is chloride contamination, which caused corrosion of reinforcing steel. A secondary cause is inadequate cover of very permeable concrete. Only after the cause and effect are evaluated, can a durable repair program be designed. If the repair program require only replacement of spalled and delaminated concrete with repair material, without considerations of inadequate concrete cover, chloride intrusion, etc., the repair will be a short term solution.

Strategies

Five strategies to provide durable surface repairs when service/exposure conditions involve surface applied chemicals which attack the reinforcing steel, causing corrosion and related spalling:

Strategy 1

- Place durable repair material of a quality somewhat better than existing.
- Place reinforcing steel protective system(?)

The repair system is redundant. However, it is assumed that over a period of time, chemical contamination of the repair material may take place, requiring the reinforcement steel protective system to provide the primary protection.

Strategy 2

- Place durable repair material of a quality somewhat higher than existing.
- Place protective surface sealer, membrane, coating on surface.

The repair system is redundant, involving a surface applied coating. The coating will keep chemical from contacting the repair material. This strategy may require periodic maintenance. If the protective system is elastomeric and capable of bridging the cracks, additional protection to the reinforcing steel is provided.

Strategy 3

- Place enhanced repair material of a quality significantly higher than the original.

The repair system has no redundant features. The system relies on the quality of the repair material to provide all protection. Enhanced repair materials involve the use of fillers and admixtures that reduce permeability.

Strategy 4

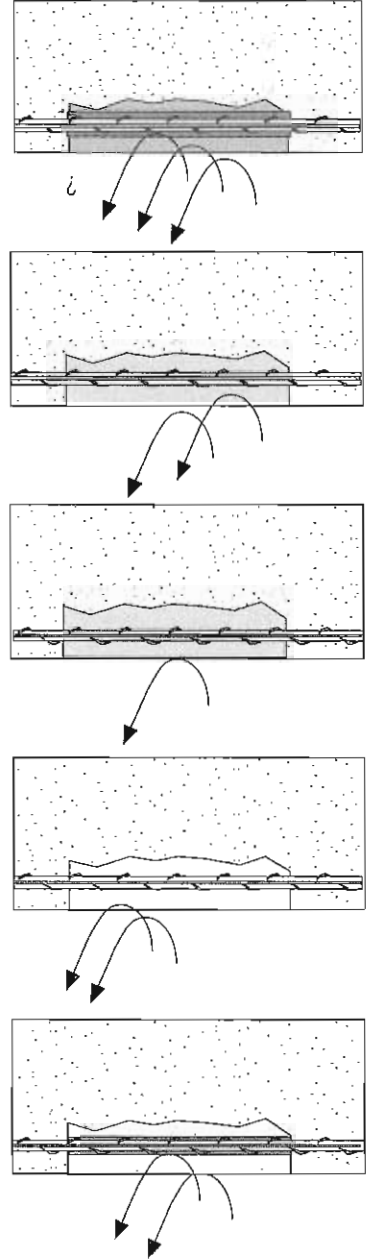
- Place enhanced repair material of a quality significantly higher than the original.
- Place protective sealer, membrane, coating on surface.

The repair system is redundant with a primary barrier coating system applied to the surface. Any failure of the barrier will result in the enhanced repair material providing protection. This system may require periodic maintenance.

Strategy 5

- Place enhanced repair material of a significantly higher quality than the original.
- Place protective sealer, membrane, coating on surface.
- Place reinforcing steel protective system(?)

This strategy involves two redundancies. The primary barrier coating provides necessary protection until failure. Upon failure, the enhanced repair material and reinforcing steel protection assume responsibility.



Additional Sources of Information

Johnson, S.M., Deterioration, Maintenance and Repair of Structures, McGraw-Hill Book Co., New York, 1965.

Evaluation and Repair of Concrete Structures, Engineer Manual EM 1110-2-2002, U.S. Army Corps of Engineers, 1986.

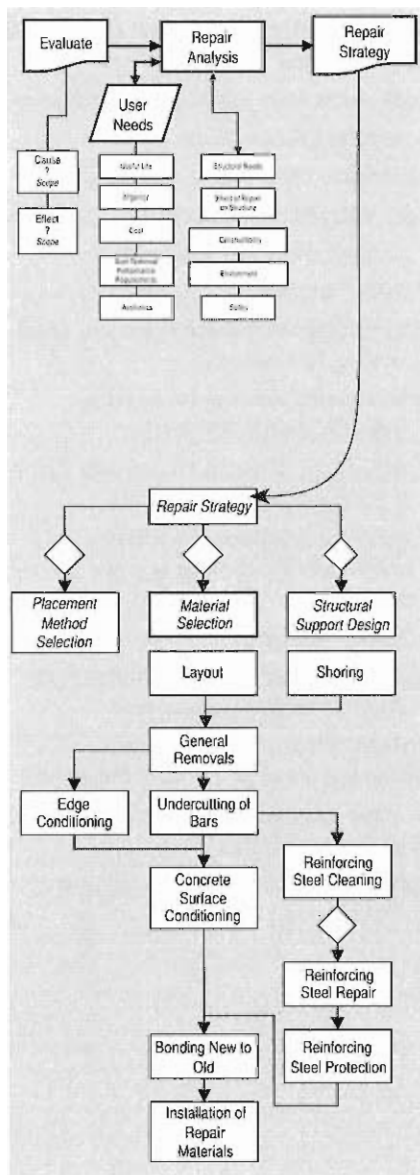
Section 2:

Material Requirements

The following topics are covered in this section:

Introduction to Material Requirements
Selection Process Flow Chart
Checklist, User Needs
Checklist, Service/Exposure Conditions
Checklist, Placement Conditions
Establishing Material Properties:
Establishing Material Properties: Load Carrying Properties
Establishing Material Properties: Service/Exposure Properties
Establishing Material Properties: External Load Properties
Establishing Material Properties: Constructibility & Appearance Properties
Volume Change Effects: Introduction
Volume Change Effects: Summary of Volume Change Mechanisms
Volume Change Effects: Drying Shrinkage Process Desired Properties
Volume Change Effects: Selecting Low Shrinkage Materials
Additional Sources of Information

Introduction to Materials Requirements



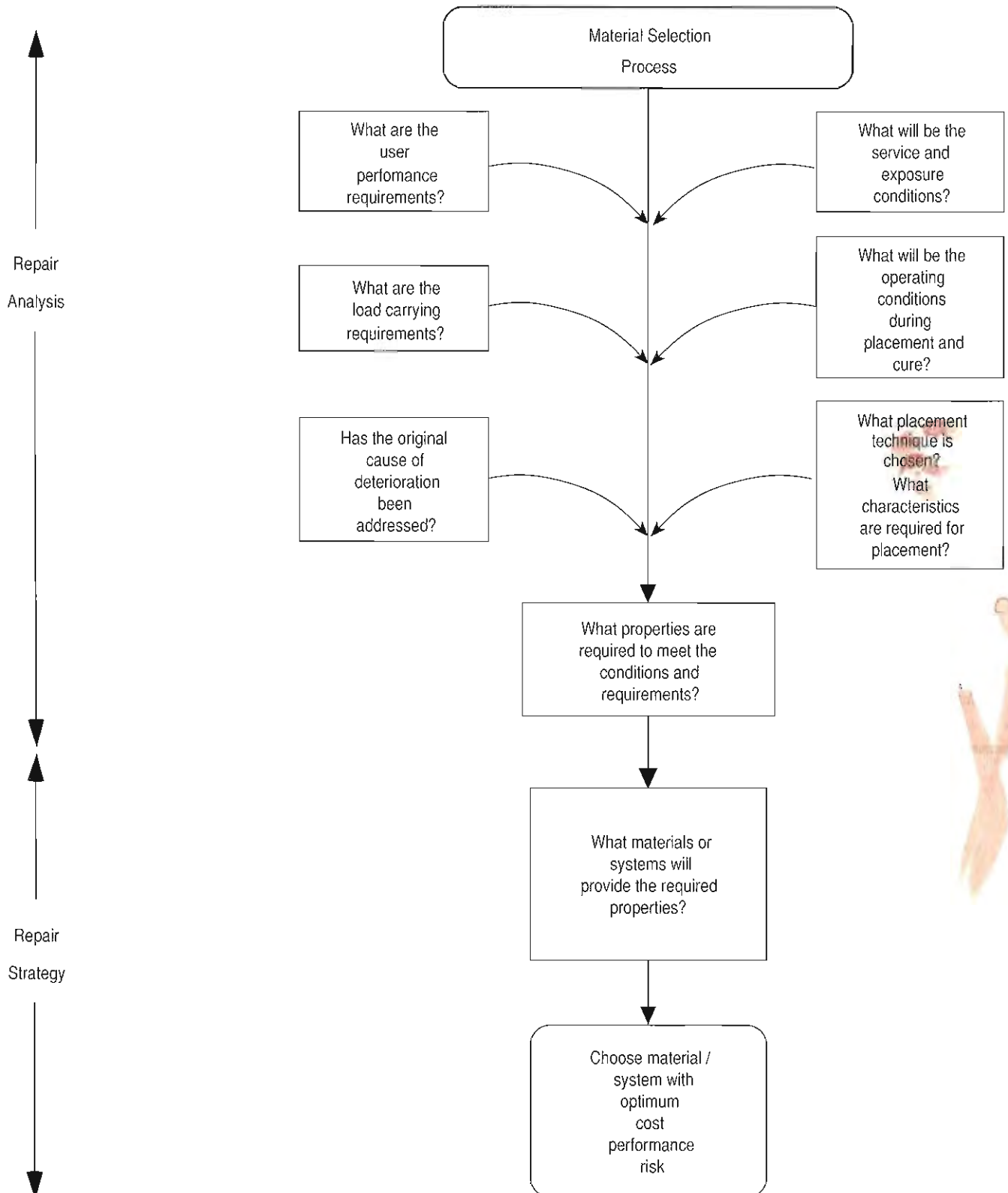
Establishing Criteria for Surface Repair Materials

Selecting repair materials for surface repair is an important and complex process involving an understanding of what is required of the repair by the owner (user) and engineer, service and exposure conditions, and installation technique. After requirements are established and material properties are defined, the selection of specific materials can be made. In some instances, more than one material or system of materials will satisfy the established requirements. Final selection of materials is made based on the relationship between cost, performance and risk.

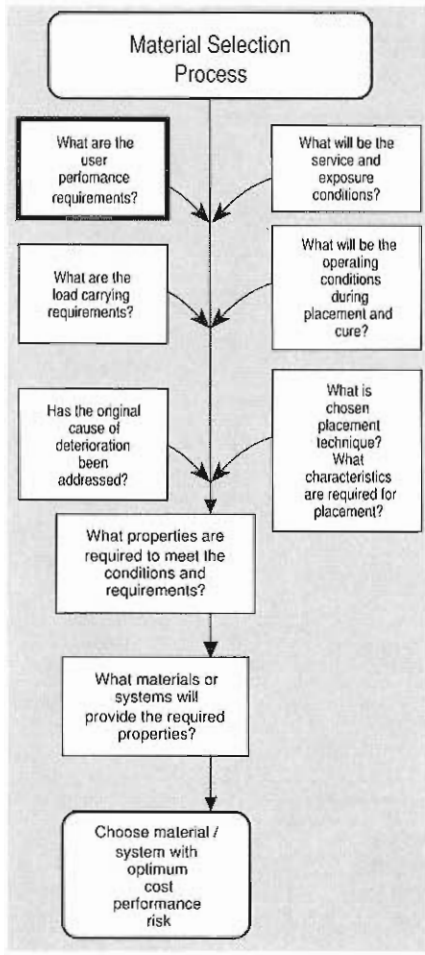
Selecting repair materials requires an understanding of material behavior in the uncured and cured states in the anticipated service and exposure conditions. One of the greatest challenges facing the successful performance of repair materials is their dimensional behavior relative to the substrate. Relative dimensional changes cause internal stresses within the repair material and within the substrate. High internal stresses may result in tension cracks, loss of load-carrying capability, delamination or deterioration. Particular attention is required to minimize these stresses and to select materials that properly address relative dimensional behavior.

Another difficult challenge is selecting surface repair materials for structural (load-carrying) applications. Many would like the new repair material to assume the stress level which existed originally. There are two obstacles to achieving 100% repair efficiency (repair efficiency = amount of stress carried by repair as compared to original concrete stress level). First, how is the repair material loaded initially? Are loads removed from the structure during repair? Second, how will the dimensional behavior relative to the substrate affect the repair's stress level? It is unlikely that one will find materials that fill the repair cavity completely, do not shrink during cure, and behave in the same way as the substrate when subjected to loads, temperature and moisture change. Selecting materials is a job of compromise!

Selection Process Flow Chart



Checklist, User Needs



What is the required appearance?

	Yes	No	Comments
Repair hidden			
Repair visible			
Crack free			
Surface texture			

How will the repair work interfere with the use of structure?

Turn around time

What is *expected life* of repair?

How long

Maintenance interval

What is tolerance for a repair failure?

Type of failure—

☐ cracking ☐ disintegration ☐ delamination ☐ separation

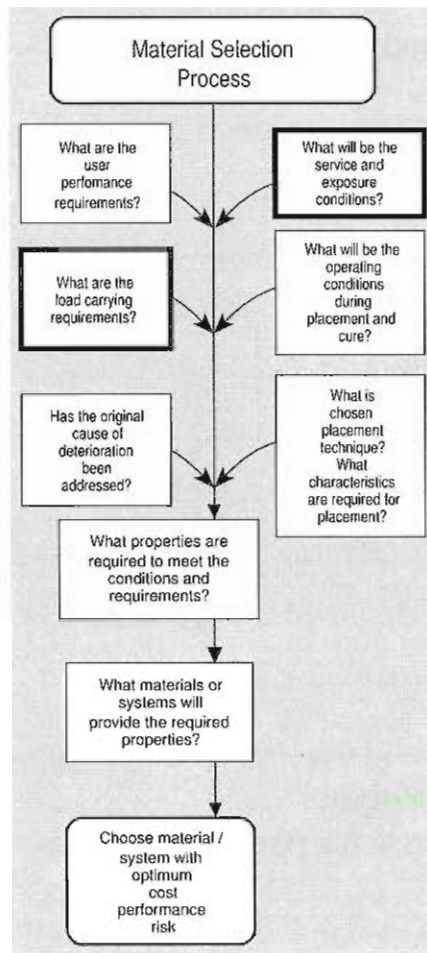
Effect of failure on personal injury

Effect of failure on process interruption

Effect of failure on structural performance

Effect of failure on environment

Checklist, Service/Exposure Conditions



What are the load carrying requirements?

Dead loads

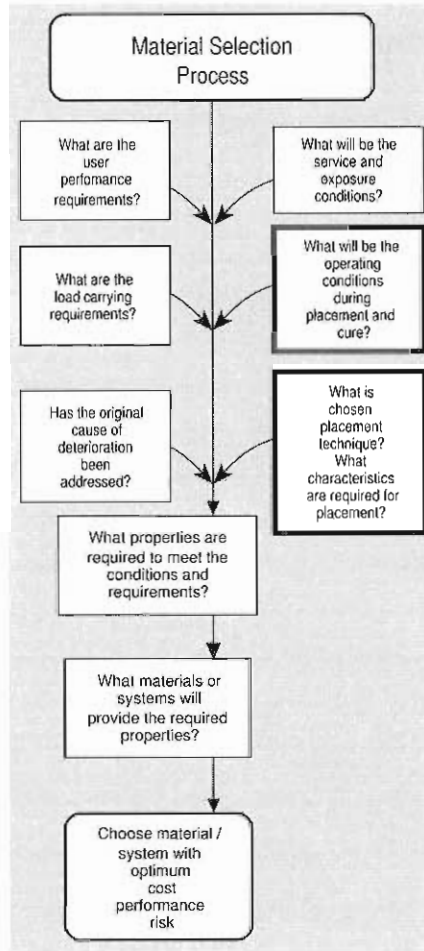
Live loads

Refer to surface repair analysis, strategy and design section.

What will be the service/exposure conditions surrounding the material?

Atmospheric gases <input type="checkbox"/> Yes <input type="checkbox"/> No	Type			
	Concentration			
	Duration			
Chemicals in contact <input type="checkbox"/> Yes <input type="checkbox"/> No	Frequency			
	Type			
	Concentration			
UV exposure <input type="checkbox"/> Yes <input type="checkbox"/> No	Duration			
	Frequency			
	Moisture conditions <input type="checkbox"/> Yes <input type="checkbox"/> No	Duration		
Temperature <input type="checkbox"/> Yes <input type="checkbox"/> No	Frequency			
	Operating Range			
	Duration			
External loading <input type="checkbox"/> Yes <input type="checkbox"/> No	Freeze-Thaw Cycles			
		<input type="checkbox"/> Yes	<input type="checkbox"/> No	Comment
	Wheel			
	Pedestrian			
	Static			
	Impact			
	Liquids—static			
Liquids—moving				

Checklist, Placement Conditions



What will be the operating conditions during placement and curing?

Access	
Wind	Wind velocity
Temperature	Substrate
	Surrounding environment
Moisture	Substrate
	Environment
Turn-around time	
Loading	Vibrations
	Deflection

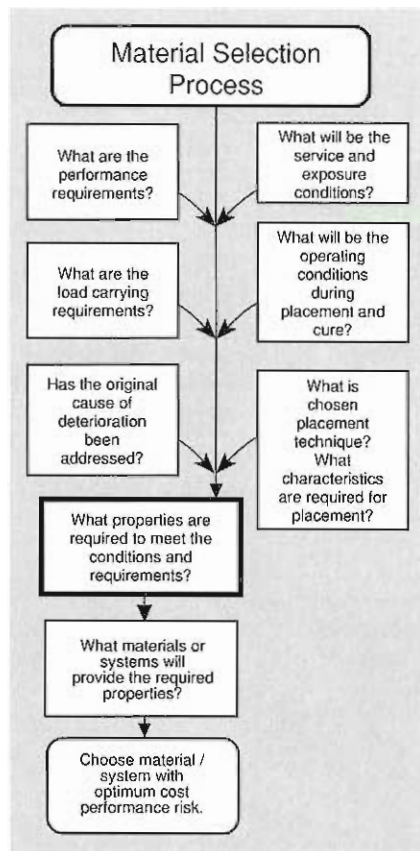
What is chosen placement technique? What characteristics are required for placement?

Flowability	
Non-sag	
Set time	

What is geometric configuration of repair?

Exposed surface area	
Thickness of repair	
Size of exposed reinforcing bars/wwf	
Spacing of reinforcing bars	
Clearance between reinforcing bars and substrate	
Clearance between reinforcing bars and exposed surface	

Establishing Material Properties

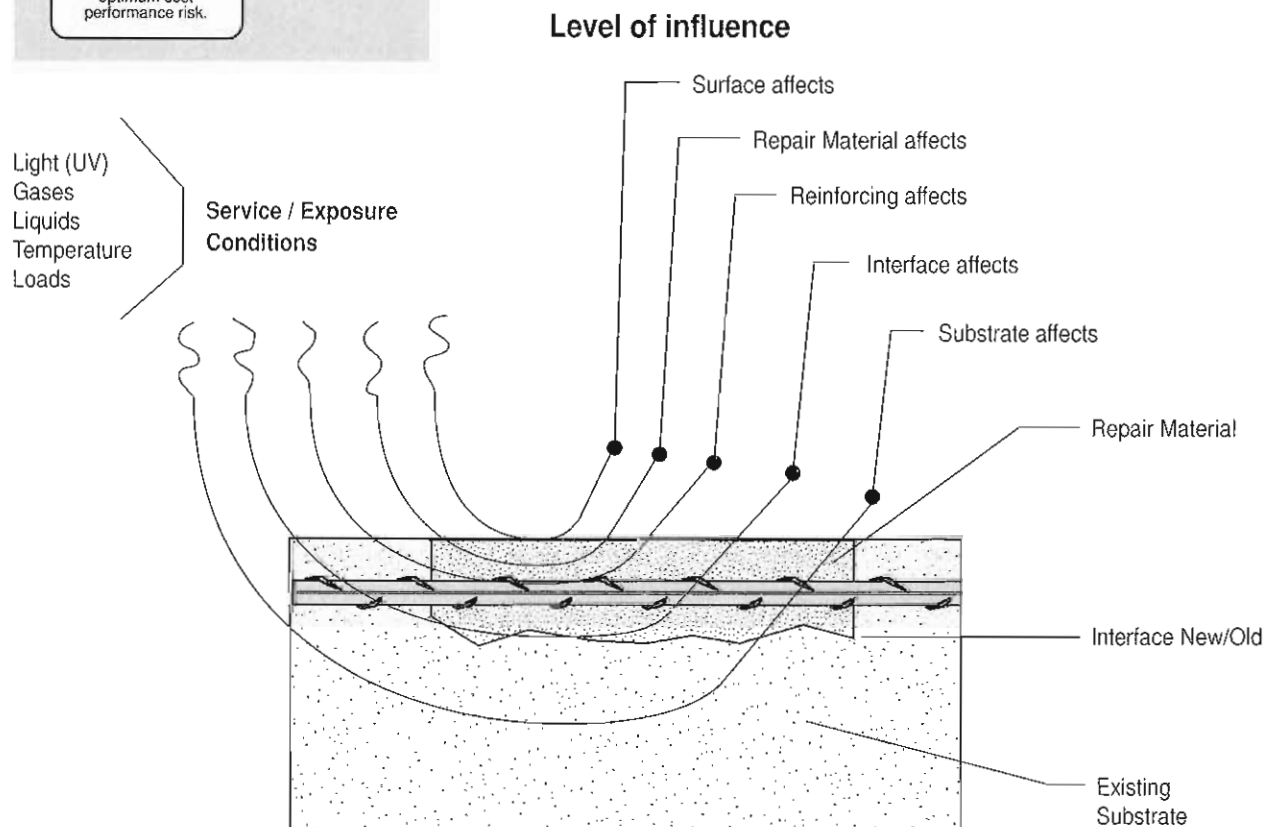


Selecting repair materials that will successfully perform under anticipated service and exposure conditions requires an understanding of how the service and exposure conditions affect the repaired member (new repair material, bond, substrate). For each service/exposure condition, a response (an effect) is generated. The response may occur at different levels (locations) within the repaired member, including the surface, repair material, reinforcing steel, bond interface and the substrate.

Example 1: Condition: Calcium chloride and moisture deposited on surface. Response: Surface of repair is subjected to chloride. Over time, the chloride will penetrate to the level of reinforcement; corrosion will result.

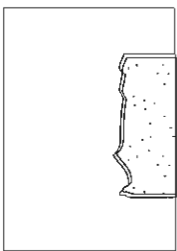
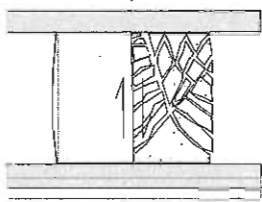
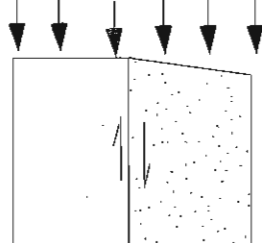
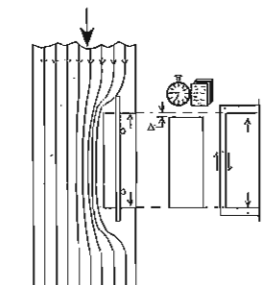
Example 2: Condition: Steel wheel load travels over repaired joint nosing. Response: Surface of repair is subjected to impact loading (local crushing at corner); repair material transfers load to bond line at substrate. (Bond is stressed; delamination may occur.)

Understanding the repair material's response to a given service/exposure condition helps in *determining required material properties* for a successful repair program. The following pages outline particular structural (load-carrying), service/exposure, constructibility, and appearance conditions typical to many repair situations. The following tables present positive and negative properties to be considered in the selection of a successful repair material.



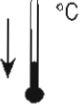
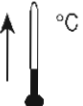
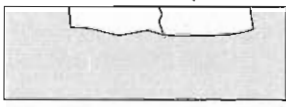
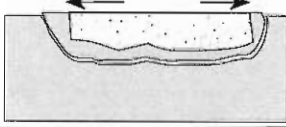




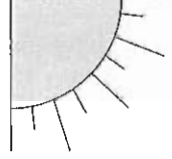
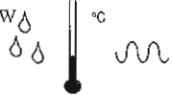

Establishing Materials Properties

Load-Carrying Properties

Goal (performance requirements)	Results if the wrong material is selected (undesirable response)	Look for these properties	Avoid these!
Bond to substrate	 <p>Loss of bond, delamination, detachment of repair from substrate</p>	Tensile bond, low internal stress	High internal stress caused by thermal incompatibility, drying shrinkage*
Load carrying as intended by the engineer	 <p>Does not carry loads as anticipated, overstressing either substrate or repair material</p>	Equal modulus of elasticity with substrate	Low or high modulus of elasticity compared to substrate
	 <p>Carries loads initially, but over time, the repair relaxes under creep deformation.</p>	Extremely low compression creep	High compression creep
	 <p>Drying shrinkage causes material to lose volume, reducing its ability to carry compressive loads.</p>	Extremely low drying shrinkage*	Shrinkage*

*Refer to Volume Change Effects included at the end of this section.

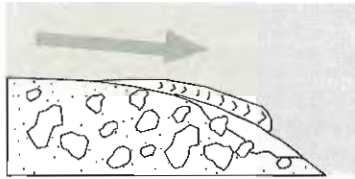

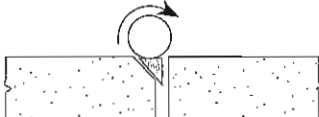
Service/Exposure Properties

Goal (performance requirements)	Results if the wrong material is selected (undesirable response)	Look for these properties	Avoid these!
Temperature changes  °C  °C	 <p>Shrinkage stresses cause cracking in repair material.</p>	Equal thermal coefficient to substrate*	Unequal thermal coefficient to substrate
	 <p>Compressive stresses in substrate causing spalling.</p>	Equal thermal coefficient to substrate*	Unequal thermal coefficient to substrate
Temperature changes in repair material during placement  °C	 <p>Shrinkage stresses in repair material causing cracking.</p>	Low exotherm during placement and cure	High exotherm during placement and cure
Atmospheric gases Moisture conditions 	Corrode reinforcing steel, disintegrate cement matrix.	Low permeability at surface or internally, no cracks	High permeability, cracking in repair material
Chemical contact Moisture conditions 	Corrode reinforcing steel.	Low permeability, at surface or internally no cracks	High permeability, cracking in repair material
	Disintegrate cement matrix.	Chemical resistance to substance at surface or internally	Lack of chemical resistance
UV exposure 	Change in mechanical properties of repair material, changes to modulus of elasticity.	High UV resistance at surface	Low UV resistance
Moisture conditions, saturation Freeze thaw cycles  °C	Dissintegration of cement matrix.	Low permeability at surface or internally	High permeability
Moisture conditions Changes in internal moisture 	Shrinkage stresses, causing cracking.	Low permeability, low drying shrinkage*	High permeability, high drying shrinkage*


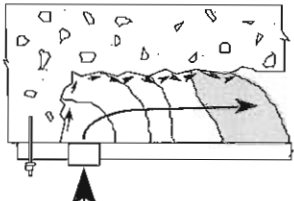
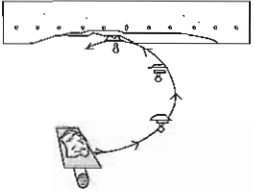
*Refer to volume change affects included at the end of this section.


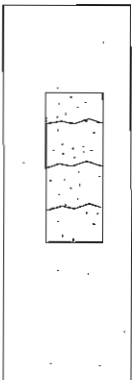
Establishing Material Properties

External Loads/Properties

Goal (performance requirements)	Results if the wrong material is selected (undesirable response)		Look for these properties	Avoid these!
Moving liquids	Erosion of surface 		High density	Low density
Moving liquids and suspended solids	Erosion and abrasion of surfaces		High compressive	Low compressive
			High tensile	Low tensile
			High density	Low density
			High compressive	Low compressive
Vehicle wheels		Abrasion damage to surface	High density, high compressive strength	Low density, low compressive strength
		Edge spalling at joints	High compressive, tensile and bond strength, tensile anchorage into substrate	Low compressive, tensile and bond strength
Impact		Spalling	High tensile strength, internal tensile reinforcement	Low tensile strength
			High compressive strength	Low compressive strength
			Low modulus of elasticity	High modulus of elasticity
		Loss of bond	High bond strength, tensile anchorage into substrate	Low bond strength

Constructibility & Appearance Properties

	Goal (performance requirements)		Look for these properties	Avoid these!
Constructibility	Turn-around time		Rapid strength gain	Slow strength gain
	Flowability		High slump	Low slump
			Small aggregate, fines, round shape	Large aggregate, angular shape, lack of fines
	Non sag		High internal cohesion, high adhesive grip	Low internal cohesion, low adhesive grip
	Forgiving "Murphy's Law"		Simple formulation, redundant	Complex formulation, dependent reactions

Goal (performance requirements)	Results if the wrong material is selected (undesirable response)		Look for these properties	Avoid these!
Appearance 		Cracking of surface from drying shrinkage*	Low drying shrinkage,* flexible surface membrane	High drying shrinkage*
		Cracking of surface in plastic stage	Low exotherm	High exotherm
			Low surface water loss during placement	High surface water loss during placement

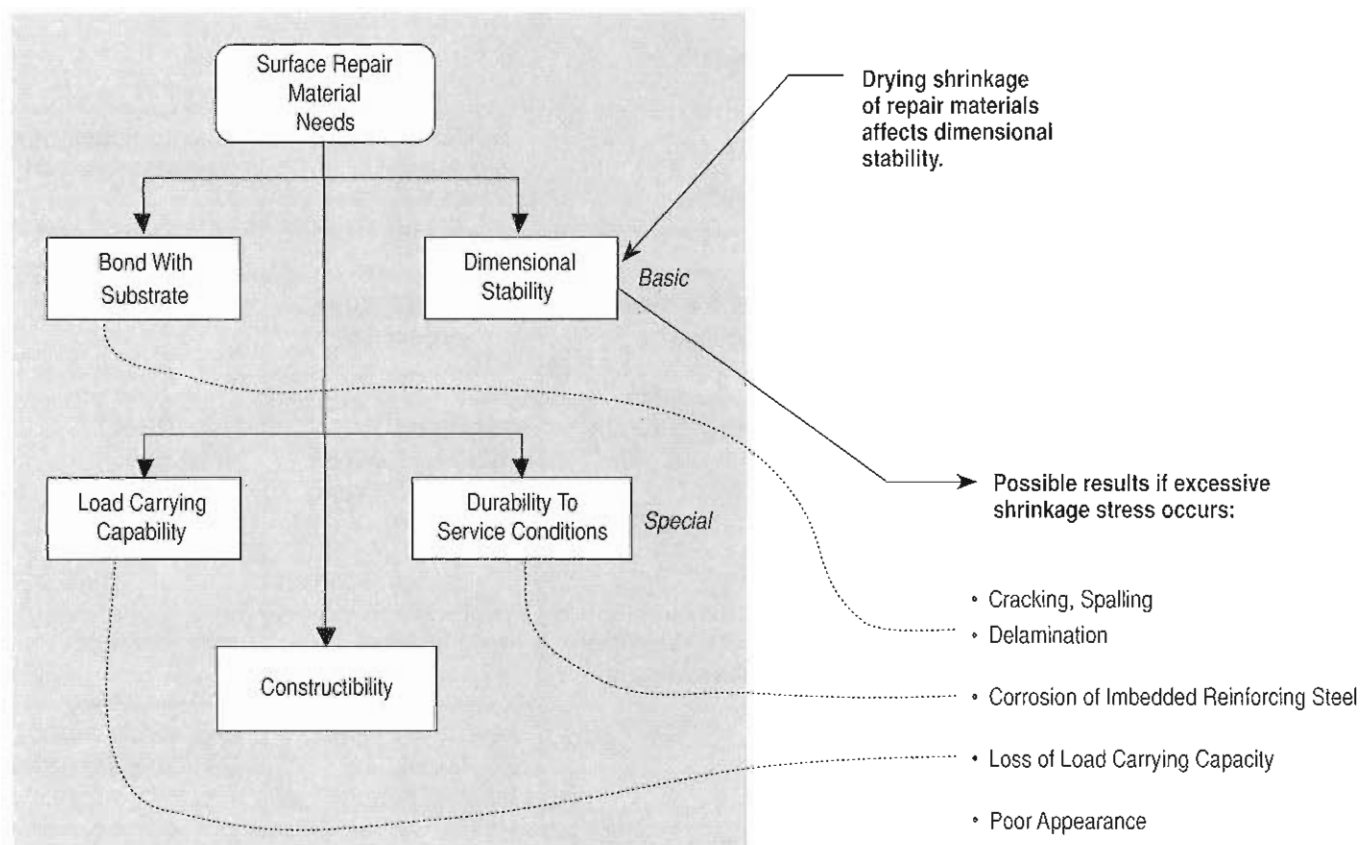
*Refer to volume change affects included at the end of this section.

Volume Change Effects

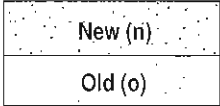
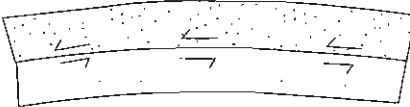
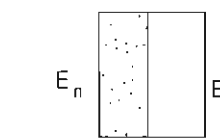
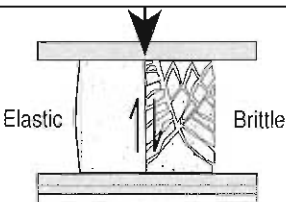
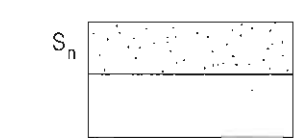
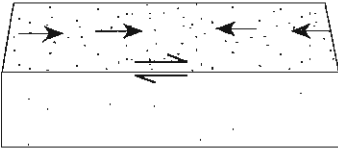
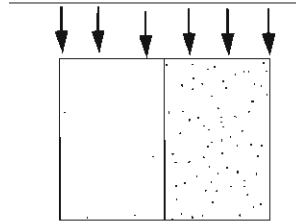
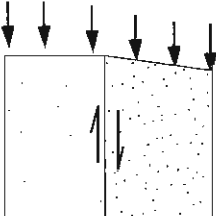
Introduction

One of the greatest challenges in the selection of repair materials is maintaining their relative dimensional compatibility with the substrate. Moisture-related volume changes in repair materials (drying shrinkage) cause many repair failures: shrinkage cracking, delamination, loss of load carrying capacity, corrosion of imbedded reinforcing steel, and poor appearance. Selection of repair materials with minimal drying shrinkage is critical for durable repairs.

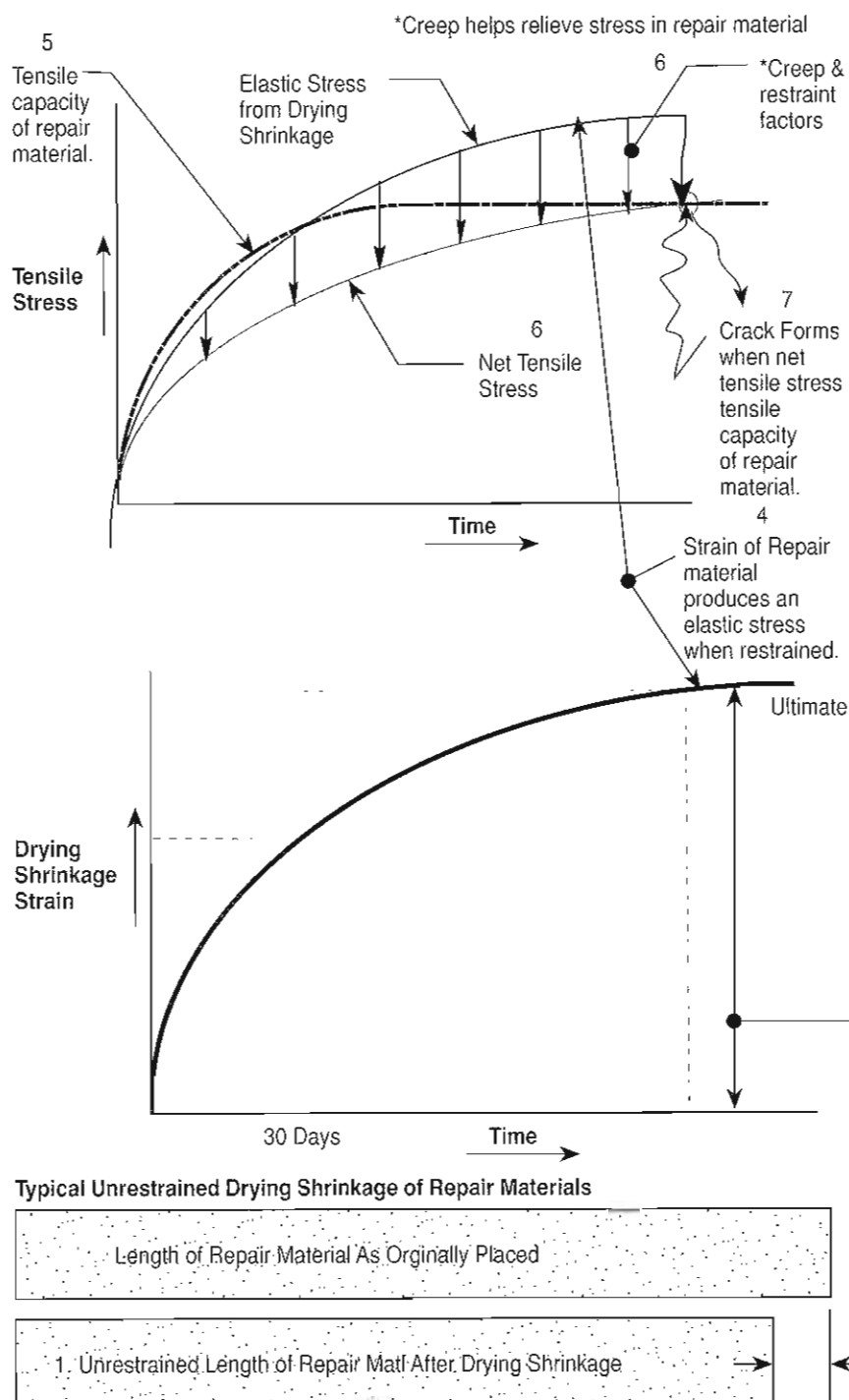
Selecting repair materials with minimal drying shrinkage requires an understanding of the drying shrinkage process. Most repair materials that are mixed and placed have an excessive amount of water above that which is required for hydration. As the repair is allowed to dry out and assume the humidity of the surrounding environment, the material shrinks in volume and tensile stress begins to accumulate in the repair material. Wet curing of cementitious materials will postpone the start of the drying process, and may cause slight expansion. The repair material resists cracking until the stress exceeds its tensile capacity (refer to accompanying illustration of the drying shrinkage process).



Summary of Volume Change Mechanisms

<div data-bbox="147 495 365 600">  <p>New (n) Old (o)</p> </div> <div data-bbox="373 506 630 600"> <p>a_n a_o</p> <p>Thermal Coefficient Of Expansion (a)</p> </div> <p>Given a temperature change evenly distributed through the materials, the following stresses will occur according to the relationship of the Thermal Coefficients of the new and old materials.</p>	<p>$a_n = a_o$ No stress occurs.</p> <hr/> <p>If $a_n > a_o$ or $a_n < a_o$</p> <div data-bbox="992 621 1399 726">  </div> <p>Shear bond is stressed.</p>
<div data-bbox="147 810 365 947">  <p>E_n E_o</p> </div> <div data-bbox="513 852 638 915"> <p>Modulus Of Elasticity (E)</p> </div> <p>Given an evenly distributed load, the following stresses will occur according to the relationship of the Modulus of Elasticity of the new and old materials.</p>	<p>If $E_n = E_o$ No stress occurs.</p> <hr/> <p>If $E_n > E_o$ or $E_n < E_o$</p> <div data-bbox="1101 894 1385 1094">  <p>Elastic Brittle</p> </div> <p>Shear bond is stressed. Brittle material may become overstressed.</p>
<div data-bbox="147 1171 440 1308">  <p>S_n</p> </div> <div data-bbox="500 1203 651 1266"> <p>Drying Shrinkage (S_n)</p> </div> <p>Assuming the old material has already developed a stable drying shrinkage volume, the following stresses will occur according to the amount of drying shrinkage of the new material.</p>	<p>If $S_n = 0$ No stress occurs.</p> <hr/> <p>If $S_n > 0$</p> <div data-bbox="1057 1266 1393 1413">  </div> <p>Shear bond is stressed. Loads carried by repair are reduced; tension in repair material.</p>
<div data-bbox="147 1533 440 1755">  <p>C_n</p> </div> <div data-bbox="472 1577 578 1608"> <p>Creep (C_n)</p> </div> <p>Assuming the old material has already developed a stable creep volume, then the following stresses will occur according to the amount of creep occurring in the new material.</p>	<p>If $C_n = 0$ No stress occurs.</p> <hr/> <p>If $C_n > 0$</p> <div data-bbox="1146 1608 1360 1822">  </div> <p>Shear bond is stressed; loads carried by repair are reduced.</p>

Volume Change Effects



Dry Shrinkage Process

1. Repair materials with drying shrinkage will contract in volume if unrestrained.
2. Drying shrinkage takes time. Most of the shrinkage will take place in the first 30 days.
3. Repair materials are not free to shrink because they are bonded to an existing substrate.
4. Since the shrinkage (strain) is restrained from occurring by the substrate, the repair material will accumulate internal tensile stress.
5. The repair material has no tensile strength when first placed, but begins to increase tensile strength as the material matures.
6. As the repair material is stretched (tensile stress) it also relaxes from tensile creep factors reducing the tensile stress to a net tensile stress.
7. The process is a "horse race" between the tensile capacity of the repair material and the net tensile stress in the repair material. If the net tensile stress exceeds the tensile capacity, the repair material will lose the race and crack.

Selecting Low Shrinkage Materials

Drying shrinkage is a critical factor in selecting repair materials for any application which requires a bonded

(integral with substrate) condition. It is necessary to select materials with low to zero drying shrinkage.

What is low shrinkage?

How do you find repair materials with low shrinkage?

These are difficult questions to answer. First, let's look at defining shrinkage for repair materials.¹ In 1987, Alberta Transportation and Utilities conducted an evaluation program for concrete surface repair materials. In this study 46 different repair materials were evaluated for various properties. One of the properties investigated was drying shrinkage. The ASTM C 157 shrinkage test was performed by one independent testing laboratory. The following chart presents test results sorted from the lowest shrinkage on the left to the highest shrinkage on the right. *Surprising Results!* By sorting the test results from low to high shrinkage, a cross section of the industry's repair materials was available for comparison. The shrinkage properties of the majority of repair materials far exceed the shrinkage value of normal weight concrete (0.05% @ 30 days²). These percentages of shrinkage do not sound large, but their effects are dramatic. Restrained shrinkage induces tensile stresses in the repair material and compressive stresses in the sub-

strate. Most repair materials have a tensile capacity of 200–1000 psi (1.4–6.9 MPa), depending upon age and design. Shrinkage of 0.025% translates into 1,000 psi (6.9 MPa) tensile stress (assuming an Elastic Modulus of 4×10^6 psi (28×10^3 MPa)).

For discussion purposes the author has taken the liberty of classifying shrinkage of materials in three basic categories: low, moderate and high. Any material with shrinkage of less than normal weight concrete (0.05%) is called *low shrinkage*. Materials with shrinkage between 0.05% and 0.10% are called *moderate shrinkage*. Materials with shrinkage greater than 0.10% are called *high shrinkage*. At the present time, the industry cannot require the manufacturers of repair materials to meet a certain maximum shrinkage value because the basis for acceptable shrinkage value has not been established.

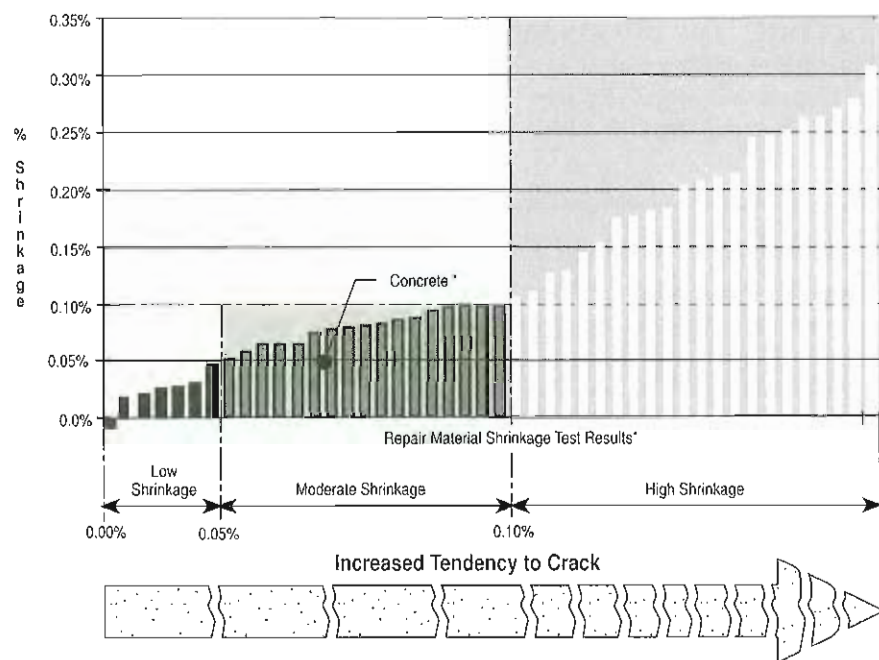
However, it is obvious that the goal for designing a surface repair material's drying shrinkage properties should be 0.00%.³

¹Carter, P. Gurjar, S., Alberta Concrete Patch Evaluation Program, Alberta Transportation and Utilities, Edmonton, Canada, 1987.

²*Volume Changes of Concrete*, Concrete Information, Portland Cement Association, Revised Chapter 12, Design and Control of Concrete Mixtures, p. 2.

³Emmons, P.H., McDonald, J.E., Vaysburd, A.M., Some Compatibility Problems in Repair of Concrete Structures—A Fresh Look, Proceedings, 3rd International Colloquium on Material Science and Restoration, Germany, 1992.

Volume Change Effects



Shrinkage test results, Alberta Concrete Patch Evaluation Program,
Report No. ABTR/RD/RR-87/05

		Water/Cement Ratio				
		0.4	0.5	0.6	0.7	
Aggregate/ Cement Ratio	3	.08	.12			High Shrinkage
	4	.055	.085	.105		
	5	.04	.06	.075	.085	Moderate Shrinkage
	6	.03	.04	.055	.065	
	7	.02	.03	.04	.05	Low Shrinkage

Shrinkage after 180 days in RH50%, 21°C, 5" square cross-section.
Source: Lea, P.M., *The Chemistry of Cement and Concrete*, third edition,
Edward Arnold (publishers) Ltd., 1970

Selecting Low Shrinkage Materials

Process for Screening Repair Materials for Low Drying Shrinkage:

-Select materials which demonstrate drying shrinkage close to 0.00%. Materials in the low category, 0 to 0.05%, have less risk of cracking than materials in the moderate category, 0.05% to 0.10%. Avoid materials above 0.10%, unless special conditions exist.

Recommendations for Reducing Drying Shrinkage of Surface Repair Materials:

- Use mixes with maximum aggregate content.
- Use clean, sound aggregates.
- Use aggregate size as large as practical.
- Avoid conditions that increase water demand, such as high temperature mixes.
- Use minimum required cement contents to meet strength requirements.
- Use proper wet curing techniques that provide reduced early shrinkage.
- Use placement techniques that allow for optimum aggregate loadings (size and amount).

The table at left shows the effects of various water/cement/aggregate ratios on shrinkage.

Additional Sources of Information

ACI 209R-82, Prediction of Creep, Shrinkage and Temperature Effects in Concrete Structures.

Warner, J., Selecting Repair Materials, Concrete Construction, Vol. 29, No. 10, Oct. 1984, pp. 865-871.

Plum, D.R., The Behavior of Polymer Materials in Concrete Repair, and Factors Influencing Selection, The Structural Engineer, England, Sept. 1990, pp. 337-345

Mays, G. and Wilkenson, W., Polymer Repairs to Concrete: Their Influence on Structural Performance, Katherine and Bryant Mather International Conference on Concrete Durability, ACI SP-100, Vol. 1, 1987, pp. 351-376.

Section 3: Material Selection

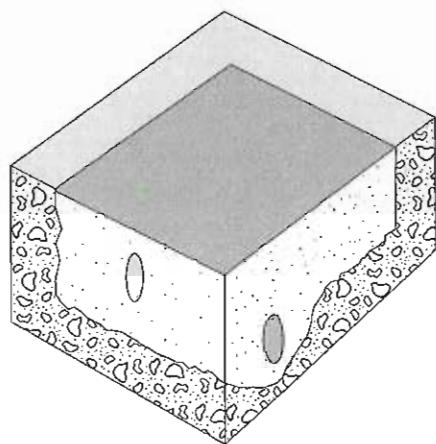
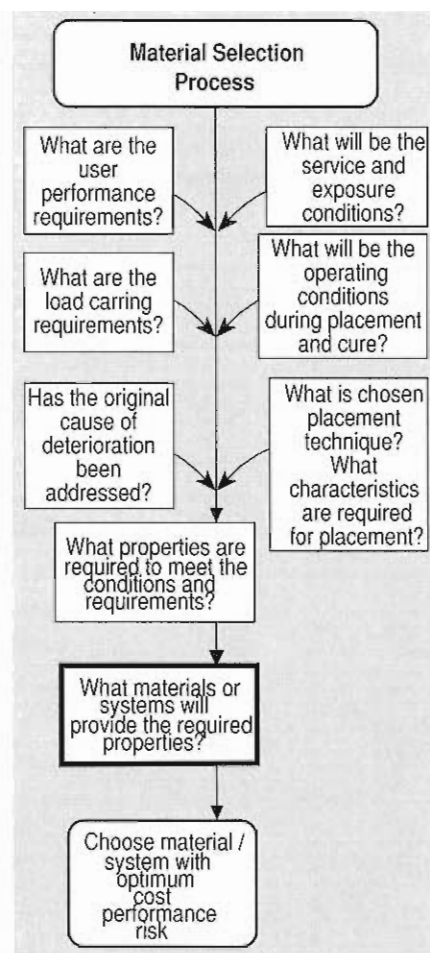
The following topics are covered in this section:

Introduction to Material Selection

Summary of Repair Materials

Repair Material Ingredients

Introduction to Material Selection



Selecting materials that meet all necessary properties established by conditions and requirements is difficult.

Some require load-carrying capability along with durability, and other situations require only durability. Most materials used for deep repairs (greater than 1.5"/38 mm) utilize portland cement binders and well proportioned aggregates. Durability for these materials can be added using special pozzolans (microsilica), polymers (latex), or admixtures that reduce permeability. Most of the latex-modified, low w/c, and microsilica-modified concretes and mortars can be easily used once one has experience in how these materials behave during placement and cure. The use of portland cement-based repair materials (site-batched, ready mix or bagged) requires special attention to shrinkage and curing. All materials should have reliable shrinkage test data to screen and select for low shrinkage materials. (See "Material Requirements" section.)

Curing of portland cement-based materials is critical in reducing early shrinkage and for future long-term performance. In structural applications, it is important to understand the repair material's response to loads. Two important properties for load-sharing applications are elastic modulus and compressive creep. Elastic modulus property can be easily obtained. However, compressive creep values are much more difficult to obtain.

It is important to understand the exposure and service conditions to which the selected materials will be subjected. It has been demonstrated that the addition of latex (SBR) to modify cement-based repair materials causes the flexural creep value to soar under high humidity (90%) conditions.¹ Most of the

reported materials creep properties evaluated under 50% relative humidity and therefore appear acceptable.

Avoid the use of materials that contain unknown ingredients or where new unproven technology is being used, except on experimental or pilot type projects. Use of materials containing gypsum results in uncontrolled expansion and extremely low durability when subject to moisture. Care should be exercised when using high exothermal materials such as magnesium phosphate-based materials. The high heat of hydration can cause thermal cooling stresses.

Other state of the art materials have been found to contain high amounts of alkali material which may result in early deterioration caused by alkali/silica reactions. Some materials are sensitive to the method of application. Latex modifiers have proven exceptional in overlays, but, when used in some applications involving dry mix shotcrete, have resulted in interbond failure. Failure was caused by latex films forming on unfinished surfaces. The shotcrete process uses high velocity air which accelerates the formation of bond-inhibiting latex film.

Polymer concretes and mortars are the other major class of materials used to repair concrete surfaces. Epoxies and acrylics blended with graded aggregates produce strong and chemically resistant materials. They can be used for thin application or thick applications where the service/exposure conditions do not cause dimensional incompatibility problems. Polymer materials have high thermal coefficients as compared to concrete. Except for thin surface coating systems, they should not be used in solar exposure situations.

The following pages outline the most common repair materials, along with their properties and limitations.

¹Plum, D.R., Materials—Why They Fail, Construction Maintenance & Repair, Sept.-Oct. 1991, England, pp. 3-6.

Summary of Repair and Overlay Materials






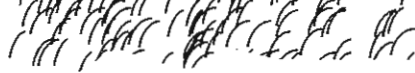


Materials	Ingredients			Application Requirements		
	Binder	Additive	Admixture	Thickness Limitation in/cm	Installation Temperature °F/°C	Curing
Portland Cement Mortar	Portland cement		Water reducer. Air-entr.	$\frac{1.5-4}{3.8-10}$	$\frac{40-90}{5-32}$	Wet 7 days
Portland Cement Concrete	Portland cement		Water reducer. Air-entr.	$> \frac{1.75}{4.4}$	$\frac{40-90}{5-32}$	Wet 7 days
Microsilica Modified Portland Cement Concrete	Portland cement	Micro- silica	HRWR Air-entr.	$> \frac{1.25}{3.0}$	$\frac{40-90}{5-32}$	Wet 7 days
Latex Modified Portland Cement Concrete	Portland cement		Latex SBR	$> \frac{1.25}{3.0}$	$\frac{45-95}{7-35}$	Wet 3 days
Polymer Modified Portland Cement Mortar with Non-sag Filler	Portland cement	Non-sag fillers	Acrylic latex	$\frac{0.25-1.5}{0.6-3.8}$		
Magnesium Phosphate Cement Concrete	Magnesium phosphate cement			$> \frac{0.75}{1.9}$	$\frac{50-100}{10-40}$	Sheet 45 min.- 2 days
Preplaced-Aggregate Concrete	Portland cement	Pozzolans	Fluidifier	$> \frac{3.0}{7.6}$	$\frac{40-90}{5-32}$	Wet 7 days
Epoxy Mortar	Epoxy resin			$\frac{0.13-0.38}{0.4-1.2}$	$\frac{50-90}{10-32}$	4 hrs.- 2 days
Methylmethacrylate (MMA) Concrete	Acrylic resin			$\frac{0.25-0.50}{0.6-1.3}$	$\frac{20-120}{-6-50}$	1 hr.- 6 hr.
Shotcrete	Portland cement	Pozzolans	Water reducer. acceler. latex	$> \frac{0.5}{1.3}$	$\frac{40-90}{5-32}$	Wet 7 days

Material Properties											Comments
* Drying Shrink- age	Coeff. of Ther- mal Expan- sion	Compressive Strength				Elastic Modulus psi/MPa	Perme- ability (Con- crete = 10)	Freeze- Thaw Resis- tance	Non-Sag Quality	Exo- therm	
		1 Hr.	1 Day	3 Days	28 Days						
Moderate	Equal to sub- strate	0	$\frac{650}{4.5}$	$\frac{2500}{17.2}$	$\frac{5000}{34.5}$	$\frac{3.4 \times 10^6}{2.3 \times 10^4}$	9	Good	Moderate	Low	
Low	Equal to sub- strate	0	$\frac{650}{4.5}$	$\frac{2500}{17.2}$	$\frac{5000}{34.5}$	$\frac{3.8 \times 10^6}{2.6 \times 10^4}$	9	Good	N/A	Low	
Low	Equal to sub- strate	0	$\frac{3000}{20.7}$	$\frac{4000}{27.6}$	$\frac{7500}{51.7}$	$\frac{4 \times 10^6}{2.8 \times 10^4}$	6	Good	Good	Low	
Low	Compat. w/sub- strate				$\frac{6000}{41.4}$	$\frac{2.5 \times 10^6}{1.7 \times 10^4}$	5	Excellent	N/A	Low	
Moderate	Compat. w/sub- strate		$\frac{1500}{10.3}$		$\frac{5000}{34.5}$	$\frac{2.5 \times 10^6}{1.7 \times 10^4}$	5	Excellent	Excellent	Moderate	
Moderate	Equal to sub- strate	$\frac{2000}{13.8}$	$\frac{6400}{44.1}$	$\frac{7000}{48.3}$	$\frac{8400}{57.9}$	$\frac{3.2 \times 10^6}{2.2 \times 10^4}$	9	Excellent	Low	High	ACI 304R-23
Very low	Equal to sub- strate	0	$\frac{500}{3.4}$	$\frac{2250}{15.5}$	$\frac{4500}{31}$	$\frac{3.8 \times 10^6}{2.6 \times 10^4}$	10	Good	N/A	Low	ACI 503.4
Low	(1.5-5) × concr.				$\frac{12000}{82.7}$	$\frac{2.2 \times 10^6}{1.5 \times 10^4}$	1	Excellent	Moderate	High	Vapor may cause problems in confined areas
Moderate	(1.5-5) × concr.	$\frac{4000}{27.6}$	$\frac{12000}{82.7}$		$\frac{12000}{82.7}$	$\frac{3 \times 10^6}{2 \times 10^4}$	1	Excellent	N/A	High	
Moderate	Equal to sub- strate	0	$\frac{800}{5.5}$	$\frac{3500}{24.1}$	$\frac{5000}{34.5}$	$\frac{3.8 \times 10^6}{2.6 \times 10^4}$	6	Good	N/A	Low	ACI 506R-90

*Drying shrinkage: Low < 0.05%
Moderate 0.05%-0.10%
High > 0.10%

Note: The material properties shown in this table vary from manufacturer to manufacturer and are shown for comparison purposes only.

Repair Material Ingredients

Ingredient	Description	Benefit
<p>Binder</p> 	<p>The binder is glue that binds all fillers and aggregates together to form a composite material. Binder materials include: Portland cement, other hydraulic cements, epoxy, acrylics.</p>	<p>Portland cements are used for most general repair work. Polymer materials such as epoxy and acrylics are used for special applications requiring chemical resistance, or very thin applications.</p>
<p>Fine Aggregate</p> 	<p>Aggregates are used to reduce binder volume and enhance mechanical properties. Fine aggregates may be used without the addition of large aggregates.</p>	<p>Fine aggregates properly graded reduce binder content and shrinkage. Special aggregates can be used to improve abrasion resistance. The shape of aggregates affects how well the material can be compacted and finished when used with trowels.</p>
<p>Coarse Aggregate</p> 	<p>Coarse aggregates more efficiently reduce overall binder volume than fine aggregates and enhance general mechanical properties.</p>	<p>Coarse aggregates reduce drying shrinkage. Special aggregates are used to enhance abrasion resistance.</p>
<p>Special Fillers</p> 	<p>Special fillers fill in spaces left by the fine and coarse aggregates. Some fillers (flyash, microsilica) replace some of the cement required. Fillers are also used to improve internal cohesion.</p>	<p>Microsilica increases the strength and reduces permeability.</p>
<p>Polymer Modifiers</p> 	<p>Polymer modifiers are used to enhance properties of the repair material. Latex (SBR) is the most common. Other modifiers include acrylic, PVA and epoxy emulsions.</p>	<p>Some polymers enhance the properties of the repair material. Latex is used to reduce permeability and increase bond strength with the substrate, and reduce modulus of elasticity.</p>
<p>Fiber Reinforcement</p> 	<p>Plastic or steel fiber reinforcement is used to add tensile strength and toughness to the repair material.</p>	<p>Fiber reinforcement provides control of shrinkage cracking. Steel, and in some cases plastic fiber, enhance toughness to impact and abrasion.</p>
<p>Misc. Chemical Modifiers</p> 	<p>Miscellaneous modifiers are used to enhance and modify behavior of the repair material. They include: accelerators, retarders, shrinkage-compensating additives, water reducers, flowability agents, expanding agents, and air-entraining admixtures.</p>	<p>Use of modifiers allows control of some properties of the uncured and cured materials.</p>
<p>Repair Material</p> 	<p>The repair material is a blend of binders, aggregates, fillers, and enhancers optimizing effectiveness, constructibility, durability, and predictability.</p>	<p>Material design should be kept simple. Do not use more ingredients than necessary. More complex materials generally cause more problems.</p>

Section 4: Surface Preparation

The following topics are covered in this section:

Introduction to Surface Preparation

General Surface Preparation
Procedures

Surface Preparation: When Oxidized
Reinforcement Is Encountered

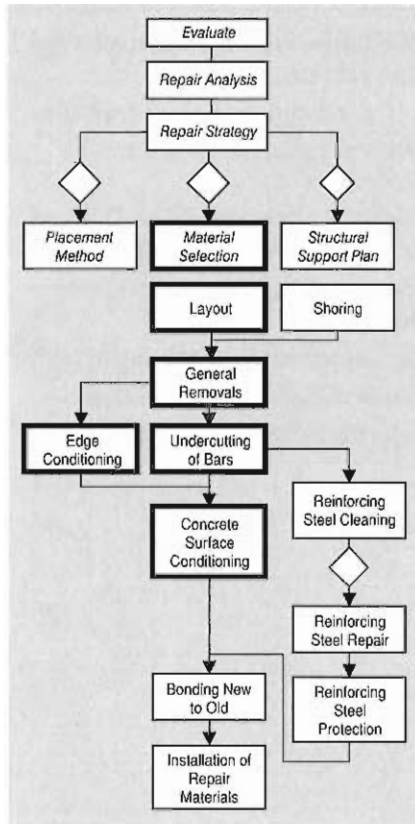
Recommended Layout of Surface
Repairs

Recommended Removal Geometry

Removal Methods: Partial Depth

Removal Methods: Full Depth

Introduction to Surface Preparation

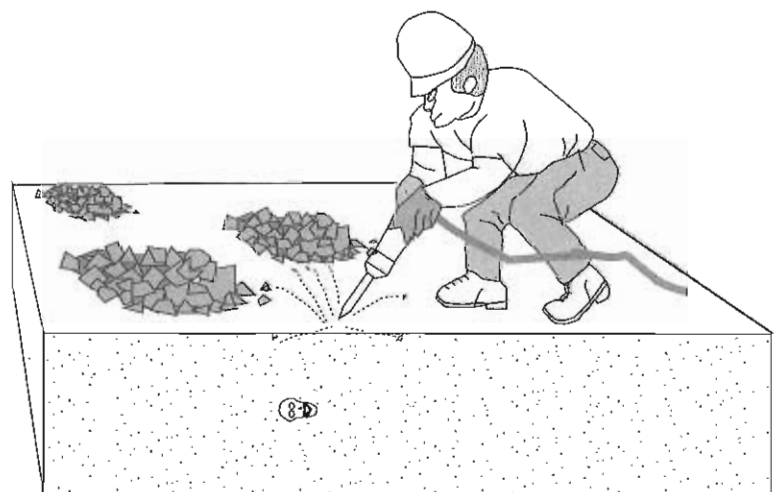


Surface repair involves the process of conditioning the existing concrete to receive repair materials. Conditioning is required to remove deteriorated, contaminated, or damaged concrete to provide surfaces that will promote bonding of the repair materials. The surface preparation process is one of the most critical phases of site work. Without proper understanding and care, the necessary requirements will most likely not be met.

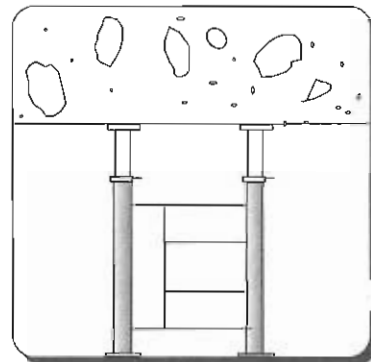
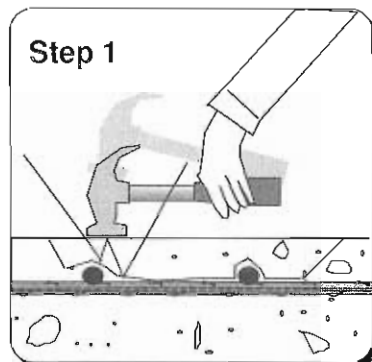
Many techniques are available to perform various aspects of concrete removal and cleaning. Each method has specific advantages and limitations. Much of the removal work is still done by small hand-held chipping hammers (15# class) because of their mobility and versatility. New technology is, however, continuously being developed. Hydromolition and hydromilling are two of the latest methods.

The quality of surface preparation may be best addressed in conjunction with the in-place repair material. Evaluation of the complete system (substrate/interface/repair material) can be accomplished by direct tension (uniaxial) pull-off testing. Performance can be evaluated qualitatively based on the location of the breaking surface and quantitatively by measuring the tension stress at failure. This procedure is discussed in the Section, "Bonding Repair Materials to Existing Concrete."

The Section, "Surface Preparation," addresses such topics as general removals, edge conditioning, undercutting of bars, and surface conditioning. Emphasis is placed on surfaces involving corroded reinforcement.

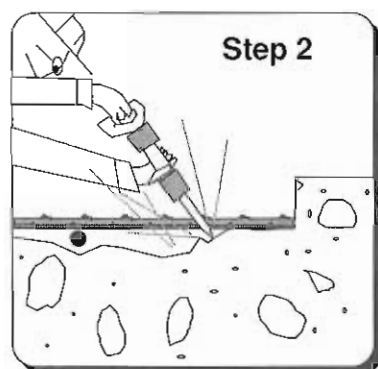


General Surface Preparation Procedure



Step 1

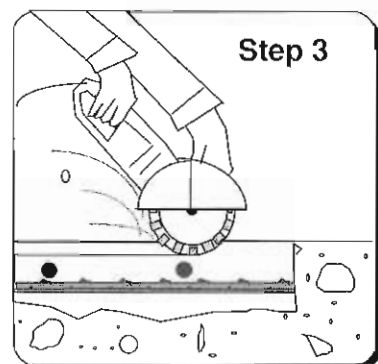
Locate area to be repaired (see "Concrete Evaluation"). Hammer sounding or chain drag are used when locating delamination. Design and install temporary support system prior to any concrete removals.



Step 2

Step 2

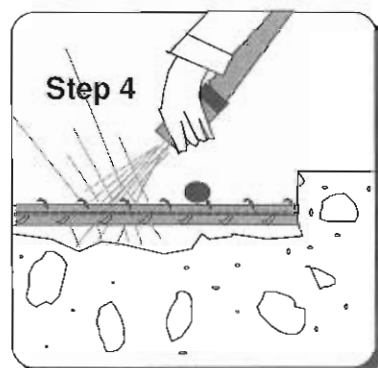
Remove deteriorated concrete using acceptable methods. When embedded steel is encountered, follow recommendations on following pages. Undercutting of exposed bars is critical to long term success of surface repairs. Bars which are damaged by the removal operation or have a significant section loss may require repair.



Step 3

Step 3

Prepare surface repair boundaries to prevent feather edged conditions. Geometry of boundaries should minimize edge length. Shotcrete may require some modifications to squared edges. (ACI 506R-90.)



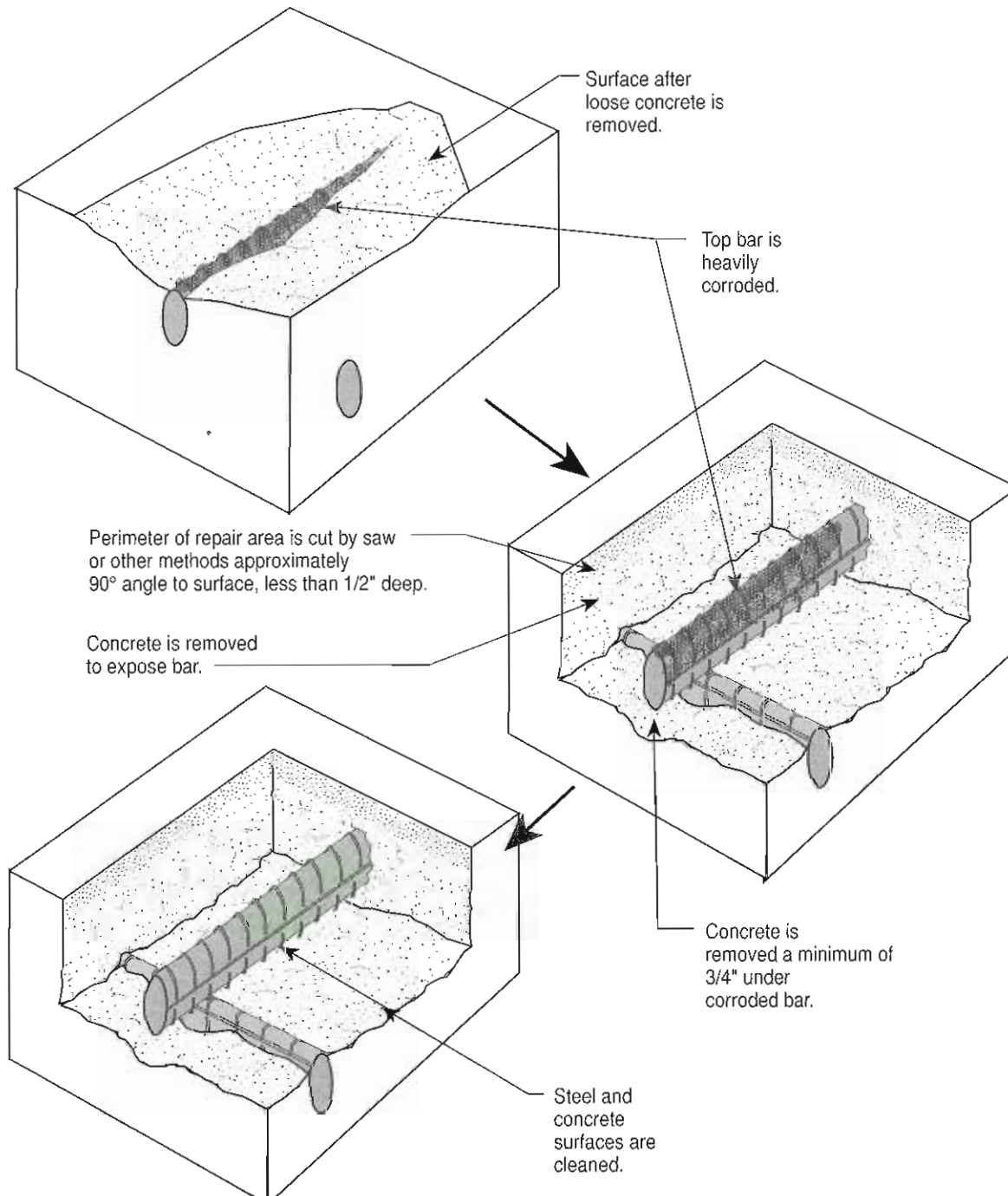
Step 4

Step 4

Clean the surface of the exposed reinforcing steel and concrete. Surface cleaning is critical to achieve an adequate bond between the repair and the existing concrete. (See "Bonding Repair Materials to Existing Concrete.")

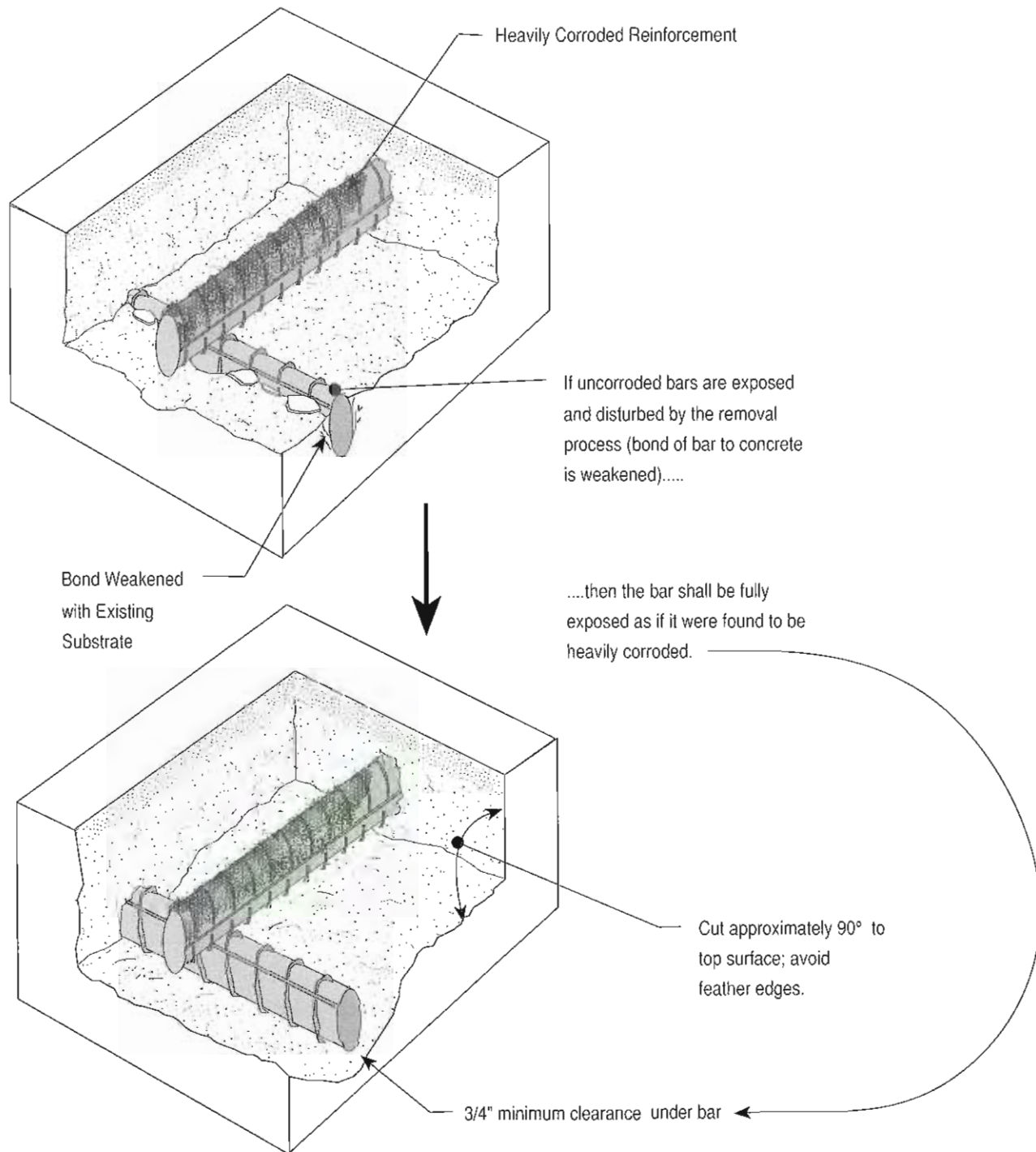
Surface Preparation

When Corroded Reinforcement Is Encountered



Adapted from IACRS—*Surface Preparation Guideline* 03730, 31, 32, 34 dated 10/15/89.

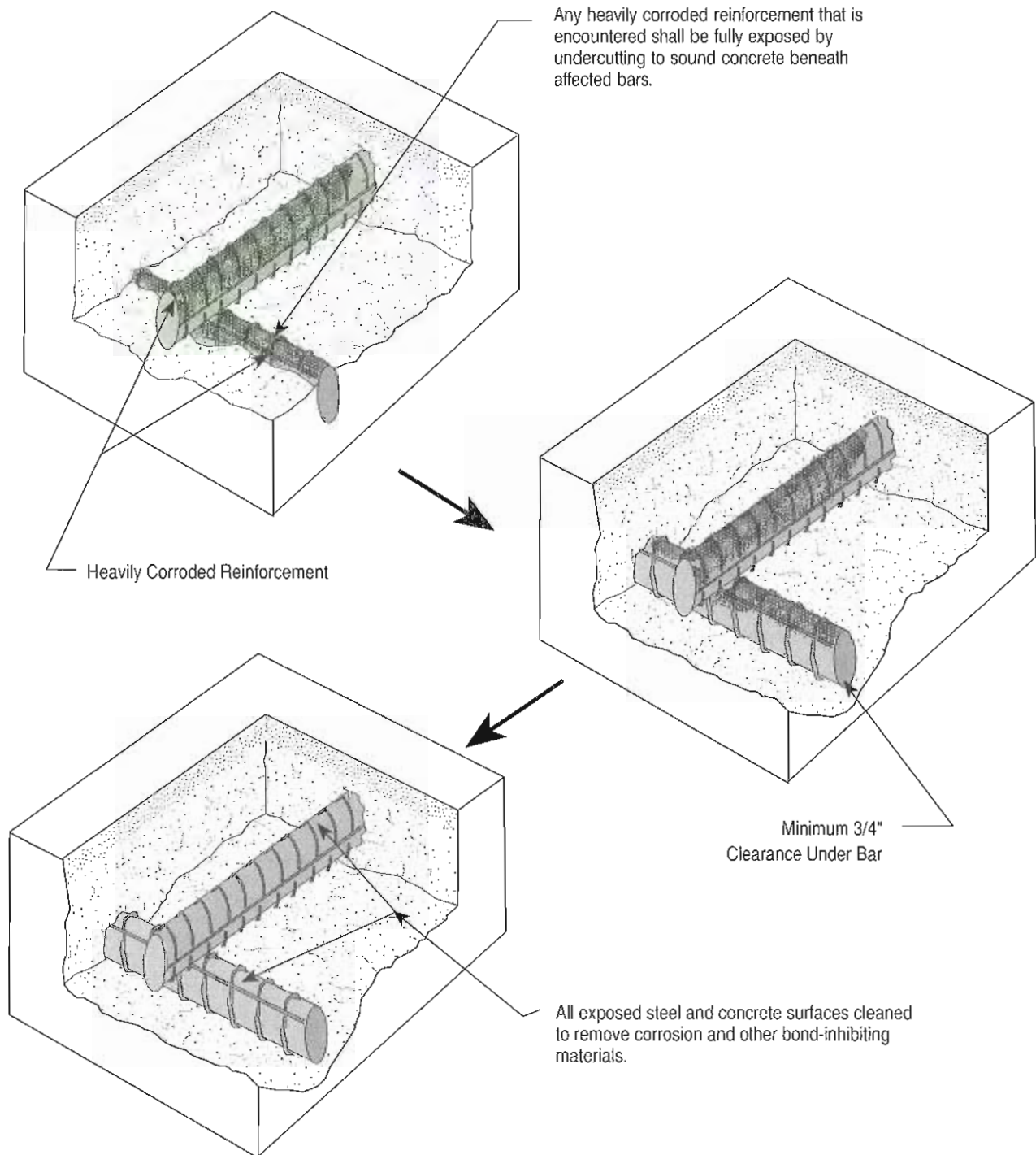
When Corroded Reinforcement Is Encountered



Adapted from IACRS—Surface Preparation Guideline 03730, 31, 32, 34 dated 10/15/89.

Surface Preparation

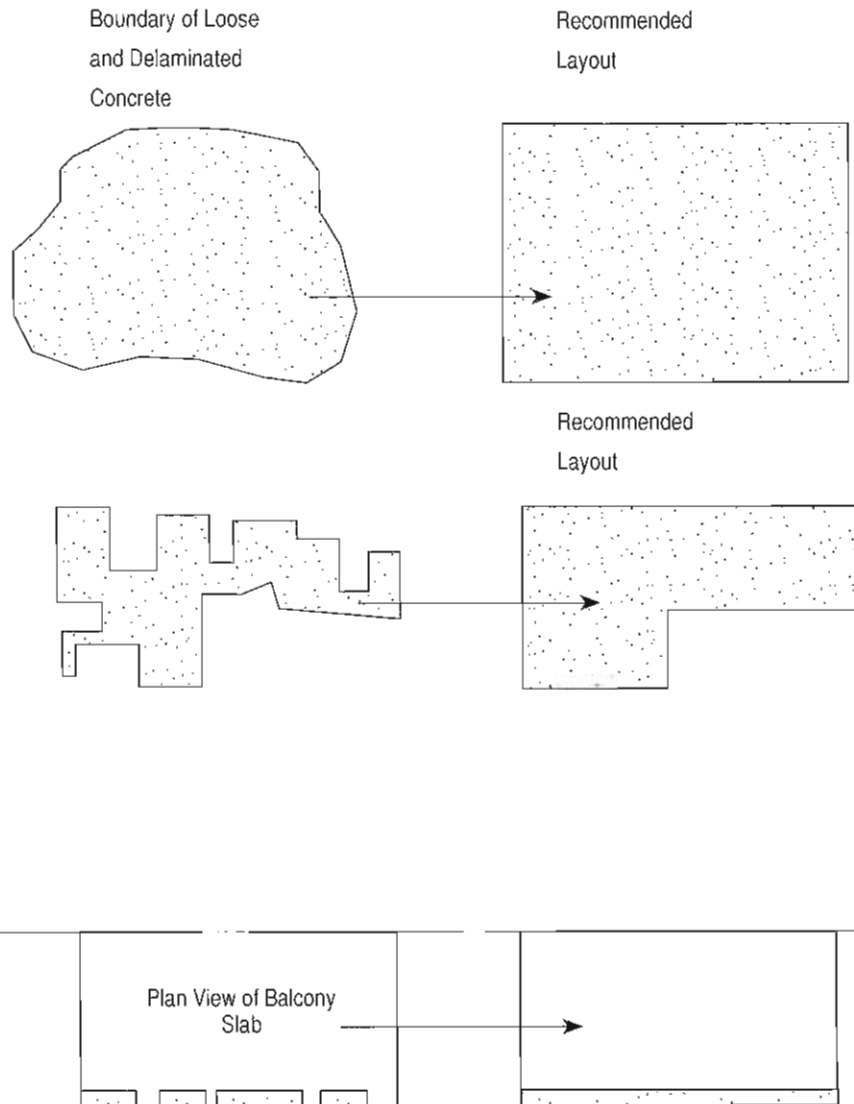
When Corroded Reinforcement Is Encountered



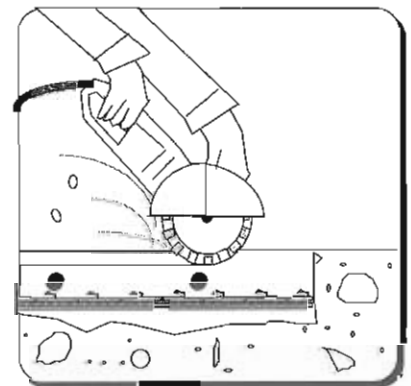
Adapted from IACRS—Surface Preparation Guideline 03730, 31, 32, 34 dated 10/15/89.

Recommended Layout of Surface Repairs

Layouts should be made as simple as possible.

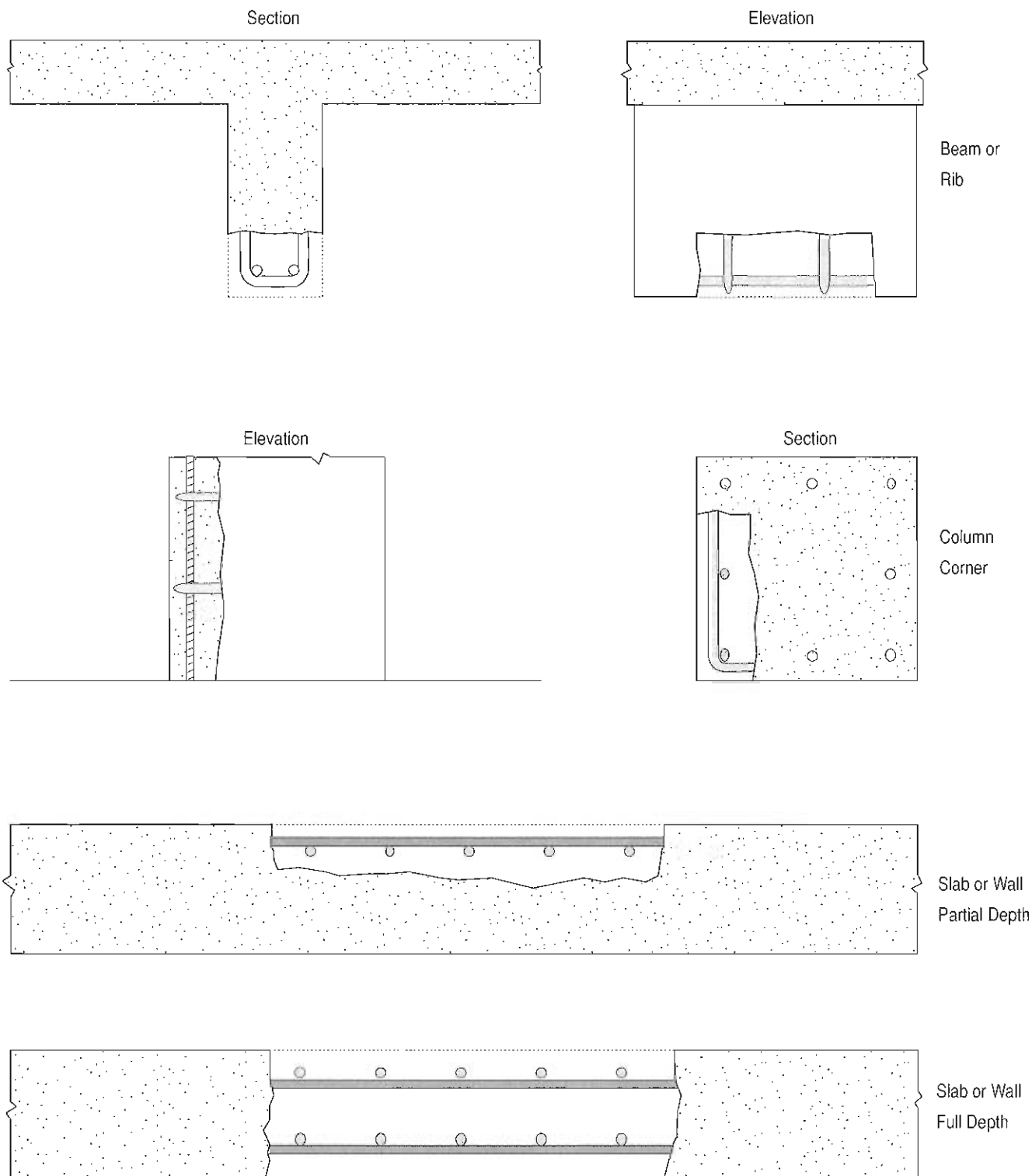


Deterioration of concrete surfaces generally is not uniform. Areas requiring repair should be modified to provide for simple layouts. The layouts should be designed to reduce boundary edge length. Excessive or complex edge conditions result in shrinkage stress concentrations and cracking. If using sawcutting as a method for edge conditioning, keep in mind that saws cut straight and that, at turns, the saw may be required to overcut.



Adapted from IACRS—Surface Preparation Guideline 03730, 31, 32, 34 dated 10/15/89.

Recommended Removal Geometry



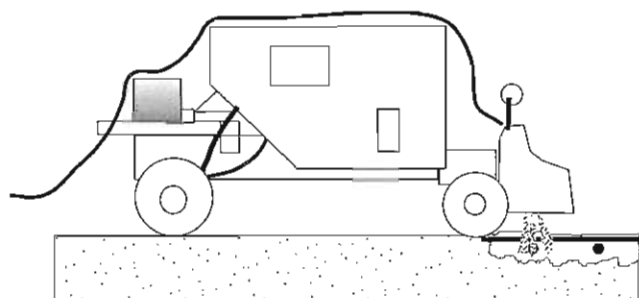
Adapted from IACRS—Surface Preparation Guideline 03730, 31, 32, 34 dated 10/15/89.

Concrete Removal Methods: Partial Depth



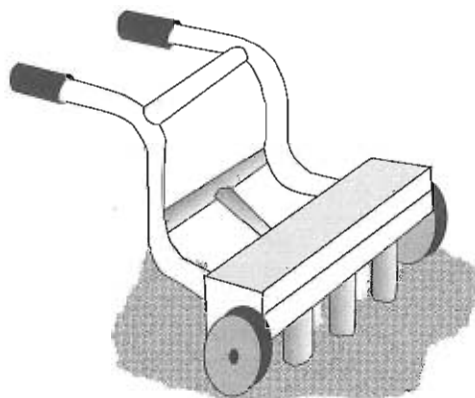
Pneumatic Chipping Hammer

The 15# to 30# class chipping hammers are the most common removal tools for surface repair. The 15# hammer is light enough for use on vertical and overhead surfaces. Chipping points are used for general removals. Hammers larger than 30# can damage encountered reinforcing steel and should be avoided for partial depth removals. Electric and hydraulic chippers are also available.



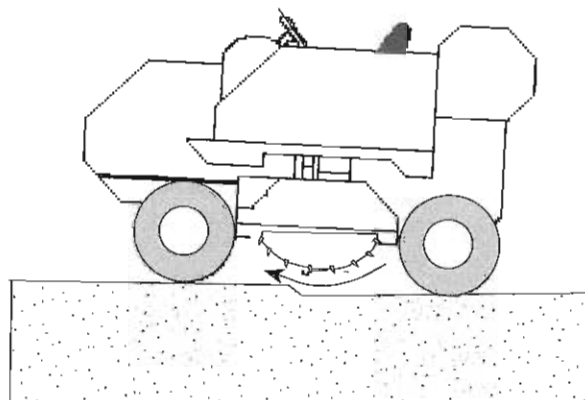
Hydro Removal

High pressure water (20,000 to 40,000 psi (138 to 276 MPa)) projected on affected concrete surfaces effectively removes concrete. Equipment is remotely controlled and mounted on a movable vehicle. Some robotic equipment can remove concrete not only on horizontal surfaces, but also on vertical and overhead surfaces. Water removals do not damage reinforcing steel. Undercutting of reinforcement can also be accomplished using this method. Cleanup of slurry and water requires extra effort.



Pneumatic Scabbler

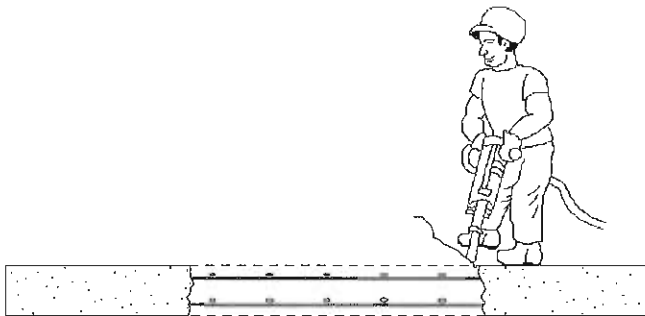
Pneumatic scabblers utilize reciprocating bushing tools hitting the concrete surface. After each hit, small amounts of concrete are removed. Pneumatic scabblers are effective tools for removing up to 1/4" (6.4mm) of surfaces for preparation of overlays. When using pneumatic scabblers, caution should be exercised to avoid bruising of the concrete surface.



Rotary Milling Machine

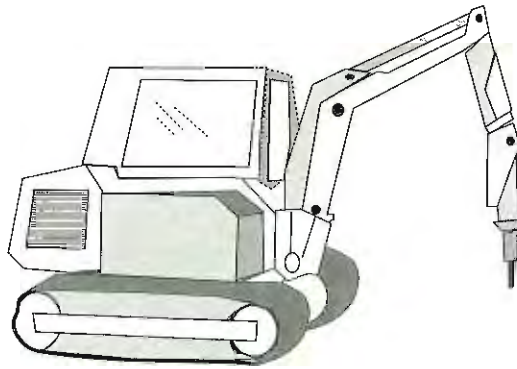
Milling machines are available in all sizes for varying field situations. Most utilize carbide-mounted tips on a rotary drum. The drum rotates, causing the carbide to chip away at the concrete surface. Milling is generally used for removing concrete surfaces in preparation for an overlay. Milling can only be used for removal of concrete down to the top surface of reinforcing steel.

Concrete Removal Methods: Full Depth



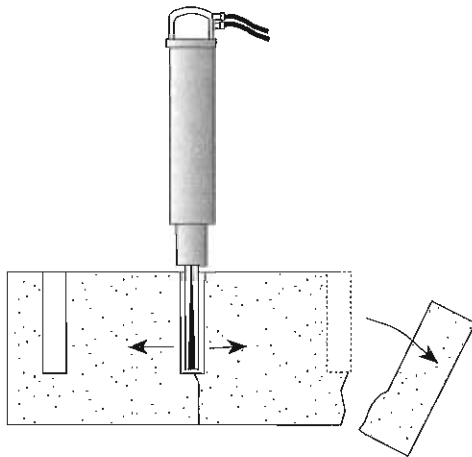
Hand Held Pneumatic Breakers

Hand held breakers 30# to 90# class are effective tools for concrete removal. Care must be taken not to damage reinforcing steel that may be encountered.



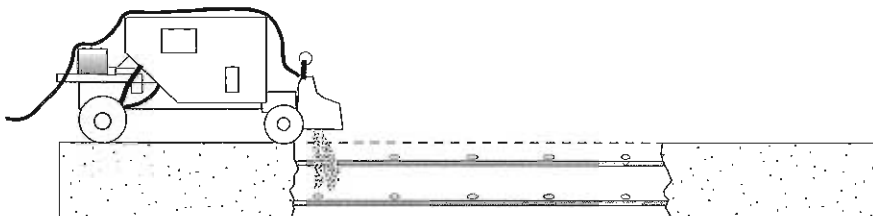
Pneumatic/Hydraulic Mounted Breakers

Mounted breakers are effective high-volume removal tools. They are generally found on backhoes, skid steer loaders, and remote-controlled robots. When using breakers, caution should be exercised to avoid bruising of the concrete surface.



Splitters

Splitters are tools used to fracture concrete into easily removable debris. Splitters are available in three types: *hydraulic wedges*, *fluid pressure*, *expansive cements*. The most common are hydraulic wedges and expansive cements. Holes are drilled for all types. Hydraulic wedges utilize steel wedges inserted into the drill hole spread via a hydraulic ram. Expansive cement is mixed with water and poured or tamped into the drilled hole. Within 24 hours, the cement expands, exerting forces great enough to fracture the concrete.



Hydro Demolition

Hydro demolition equipment utilizes high pressure water (20,000 to 40,000 psi(138 to 276 MPa)) projected on to the concrete surfaces. Full depth removals with this equipment can be effective on thin slabs.

Section 5:

Reinforcing Steel Cleaning, Repair & Protection

The following topics are covered in this section:

Introduction to Reinforcing Steel
Cleaning, Repair & Protection

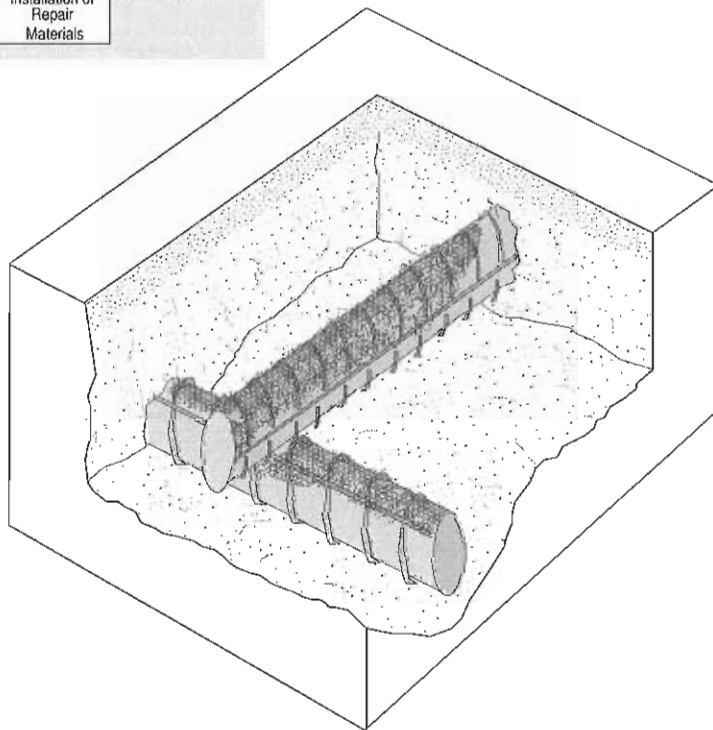
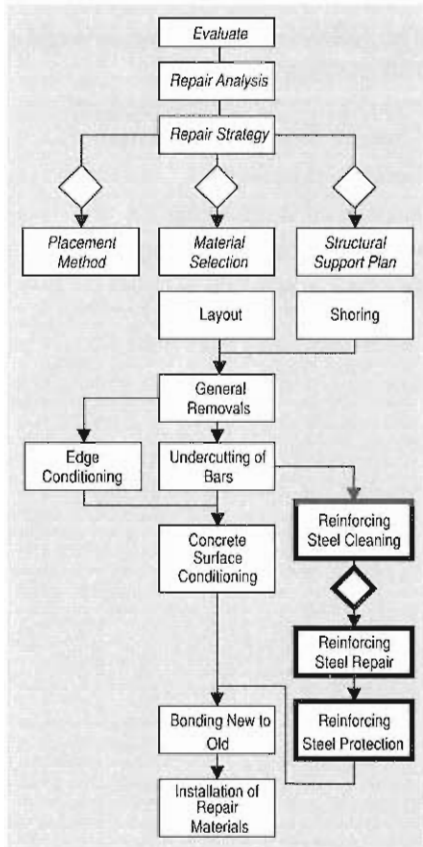
General Procedure

Reinforcing Steel Repair

Reinforcing Steel Cleaning

Reinforcing Steel Protection

Introduction to Reinforcing Steel Cleaning, Repair & Protection

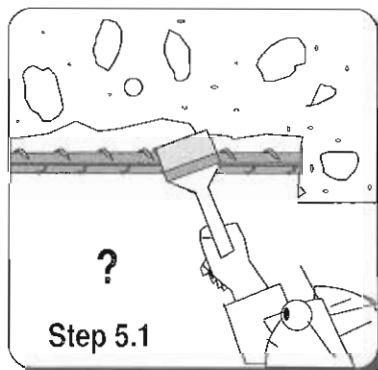
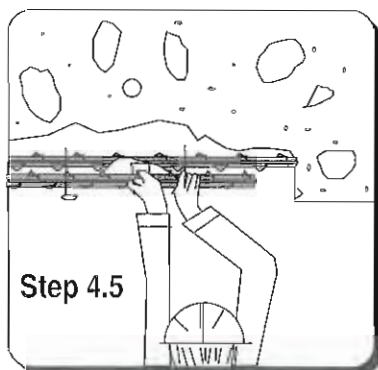
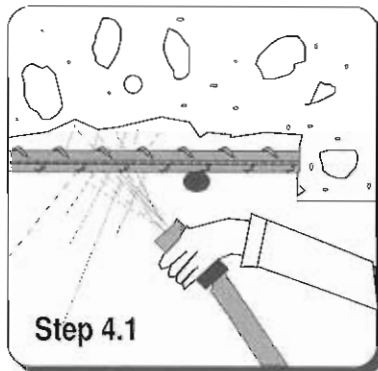
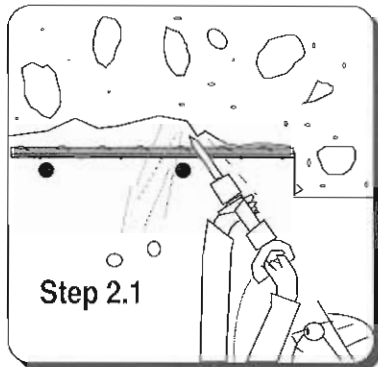


Corroded or otherwise damaged reinforcing steel is usually found in conjunction with concrete deterioration. Heavy rust layers that build up on reinforcing steel during the corrosion process are the cause of concrete delamination and spalling. Removal of oxide build-up is critical to the long term success of surface repairs. Many repairs have failed within a few years of completion because of insufficient cleaning. Proper cleaning of corroded bars requires removal of concrete around the full circumference of the bar, although in the past, practice required removal around the full circumference only when corrosion exceeded more than 50% of the circumference. By removing the full circumference, the contaminated concrete can be removed. Chlorides and carbonated concrete may be present around the rebar, even though corrosion is not present. Two other reasons for removing the concrete around the bar are (1) to allow the repair material to encapsulate the bar, providing a relatively uniform electrochemical environment, and (2) to anchor the repair to the substrate.

Whenever bars corrode, they also lose valuable section, thereby reducing the ultimate load carrying capacity. In some instances, bars lose all section through the corrosion process. Structural evaluation is required to understand the effects of section loss and whether repairs are required to restore it.

Common sense would seem to recommend placing protective coatings or using other means to prevent the recurrence of corrosion. However, quality concrete is generally all that is necessary to protect embedded reinforcing steel. While the current practice of protecting exposed bars is controversial, many systems are available. Several protective systems are discussed in this section.

General Procedure



Step 2.1

Exposed corroded reinforcing steel encountered in the repair process requires concrete to be removed around the full circumference of the bar. This allows the reinforcing bar to be cleaned and allows a uniform material to be placed around it.

Step 4.1

Heavy oxides or other bond-inhibiting materials must be removed by any acceptable cleaning method. (See "Reinforcing Steel Cleaning.")

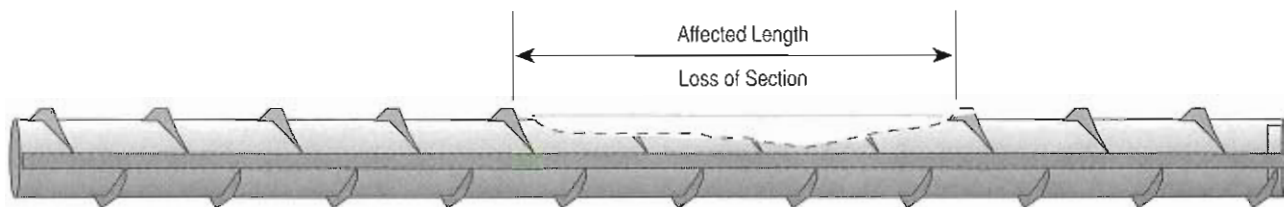
Step 4.5

Bars damaged during removal operations or with critical section loss may require repair or replacement. (See "Reinforcing Steel Repair.")

Step 5.1

In certain situations, special coatings may be applied to add additional protection to the reinforcing bars. (See "Reinforcing Steel Protection.")

Reinforcing Steel Repair (from Section Loss)

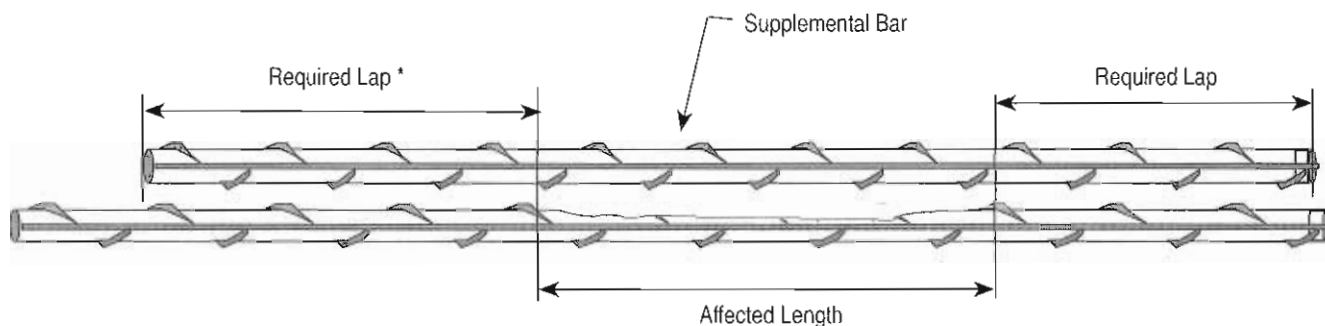


If the reinforcing steel has lost more than 25% of its cross section (or 20% if two or more adjacent bars are affected), then reinforcing steel repair is generally required.

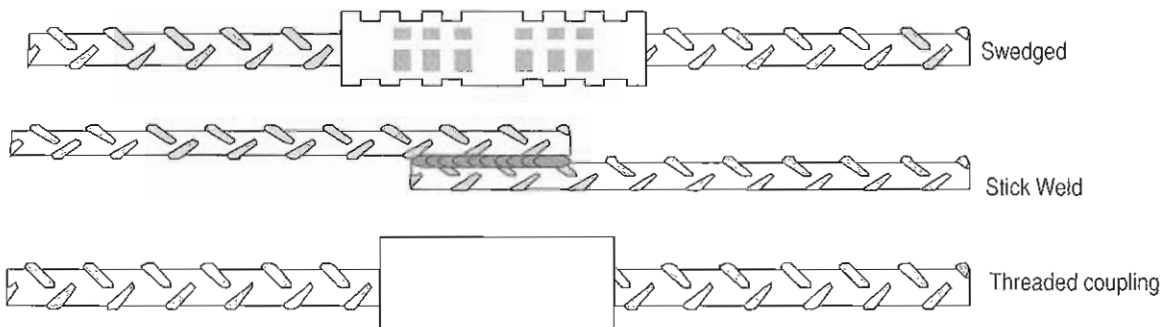
Note: When damage to reinforcing steel is uncovered, it is good practice to perform a structural review of situation.

If repairs are required for the reinforcing steel, one of the following methods should be used:

1. Supplemental bar over affected length. New bar may be mechanically spliced to affected bar or placed parallel to existing bar.
2. Complete bar replacement.



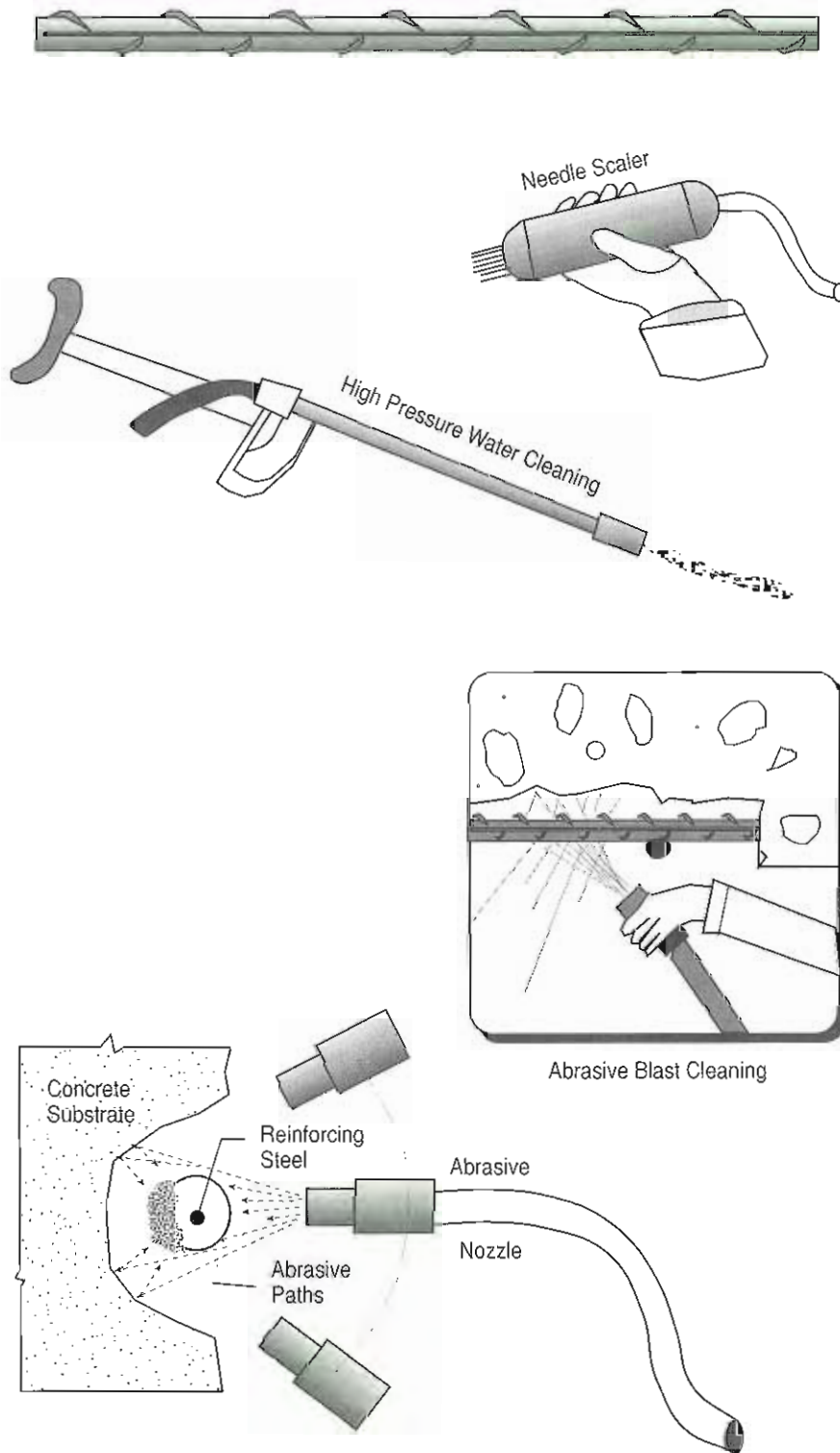
Typical Splice Methods



* Lap length shall be determined in accordance with ACI 318; also refer to AASHTO and CRSI Manuals.

Adapted from IACRS—*Surface Preparation Guideline* 3730, 31, 32, 34 dated 10/15/89.

Reinforcing Steel Cleaning



General Procedure

All heavy rust and scale should be removed from the rebar to promote maximum bond with repair materials. A tightly bonded light oxide build-up may develop after cleaning. This is usually not detrimental to bond. If a protective coating is being applied to the rebar, the manufacturer's recommendations for surface preparation should be followed.

Needle Scalers

Needle scalers are pneumatic tools utilizing a group of small diameter steel rods powered by an internal piston. The steel rods hit the intended surface, causing removal of surface materials. Needle scalers are effective tools for removal of heavy oxide layers, as well as for surface cleaning of small areas of concrete.

High Pressure Water Cleaning

High pressure water (3,000 to 10,000 psi (20.7 to 69 MPa)) cleans concrete and steel surfaces, removing unsound materials. Water mixed with sand cleans faster and results in a roughened surface which will promote a better bond with coatings or with repair materials.

Abrasive Blast Cleaning

Abrasives mixed with pressurized air and projected through a nozzle are the best method of providing steel or concrete surfaces with a clean profiled surface. Airborne debris (dust) is an environmental concern when using this method. Water can be injected at the nozzle to reduce dust in this process.

Power Wire Brushing

A power wire brush is an effective tool for removing unwanted oxide from steel surfaces. Wire brushing is a very slow and ineffective operation when rebar has to be cleaned on the back side.

Adapted from IACRS—*Surface Preparation Guideline* 3731, October 15, 1989.

Reinforcing Steel Protection

Reinforcing steel is naturally protected from corrosion when surrounded by an alkaline environment of newly cast, good quality concrete. In certain repair situations, additional protection for the encased reinforcement is prudent. Protection systems fall into four (4) categories:

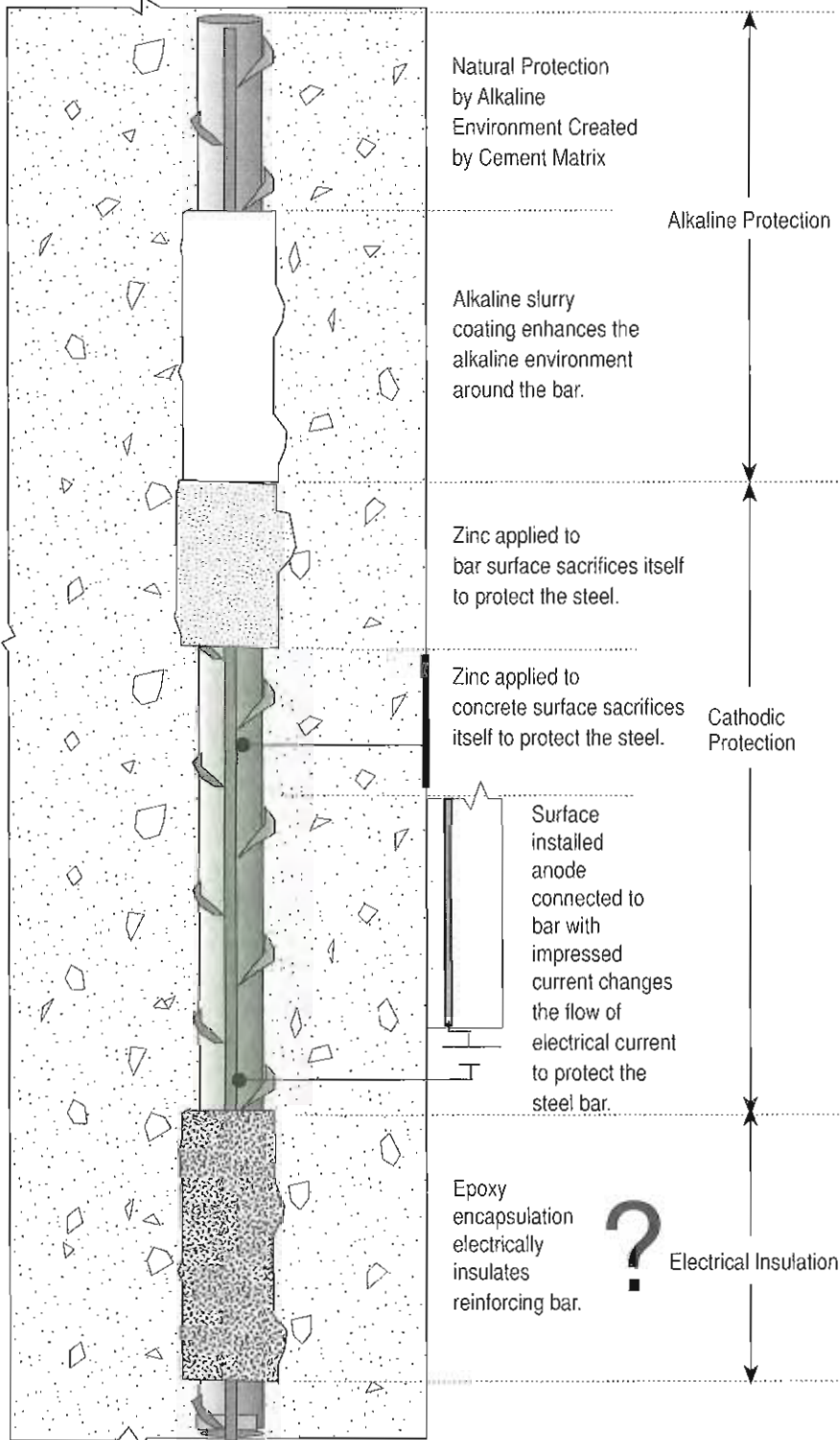
1. Encapsulation: Insulating the bar from electrical currents in the surrounding concrete can be accomplished by encapsulating the bar with epoxy. When new bars are used, fusion-bonded epoxy provides the best protection. Bars are shot-blasted and heated, and powdered epoxy is sprayed onto them under a controlled environment. In field applications where encapsulation of existing bars is necessary, epoxy resin is sprayed or, more commonly, brushed onto the bars. With field application of epoxy it is very difficult to achieve 100% coverage of the exposed bars. Intersections and back sides of bars create almost impossible access. Encapsulation works well when all bars in the affected member are protected; however, when bars are partially coated, either within the repair zone or adjacent to the repair, electrical currents can become concentrated in the unprotected bars, and accelerated corrosion may be a problem.
2. Cathodic Protection/Sacrificial Anode: Protecting bars from corrosion can be accomplished by coating them with a sacrificial metal. Zinc is the metal commonly used for this purpose. Zinc is applied to the bar with a brush. Recently, molten zinc has been used (California DOT) as a sacrificial surface-applied coating. This method is used after all surfaces are repaired. The surface-applied zinc is electrically connected to the reinforcing steel cage. Since this method is sacrificial, the service

life is dependent upon the degree of exposure to a corrosive environment and anode activity. This method of protection is used only on an experimental basis.

3. Cathodic Protection/Impressed Current: Protecting bars from corrosion can be accomplished by reversing the electrical current flow which causes the corrosion process. Anodes are installed on or near the concrete surface and are electrically connected to the reinforcing bars. Electrical current is pumped into the circuit, protecting the bars. Impressed current must be balanced with the environment on a continual basis in order to provide protection. Constant monitoring and necessary adjustments are required.
4. Alkaline Slurry Coating: Like uncarbonated concrete, alkaline slurry coating protects the reinforcing steel from corrosion. Some systems utilize non-passivating epoxies as a binder for the passivating (alkaline) fillers. Some questions exist concerning whether the epoxy insulates the alkaline fillers from direct contact with the rebars and whether the epoxy provides any benefits other than electrically insulating the bar.

There are many unanswered questions regarding reinforcement protective systems and their effect on surrounding reinforcement. By protecting reinforcing steel in a repaired area we have created an island of new material. In doing so, potentially more corrosion could occur than would have originally. Only independent research, testing and monitoring will answer these questions.

Reinforcing Steel Protection



Section 6: Bonding Repair Materials to Existing Concrete

The following topics are covered in this section:

Introduction to Bonding Repair
Materials to Existing Concrete

Measuring Bond Strength

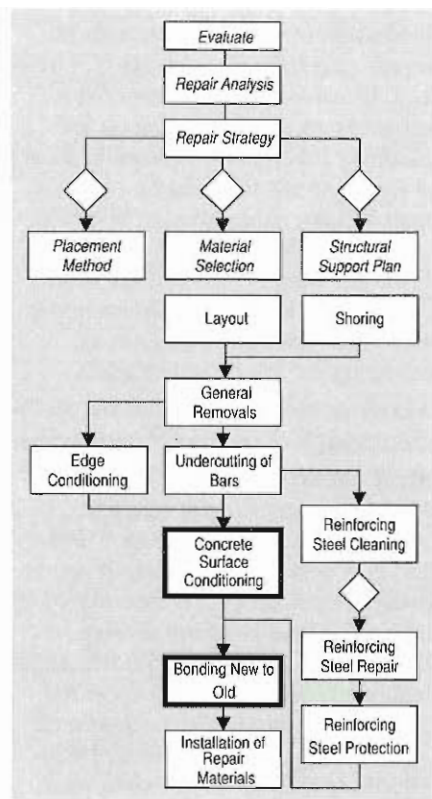
Evaluating Bond Strength

General Procedures

Bonding Agents

Additional Sources of Information

Introduction to Bonding Repair Materials to Existing Concrete



Keys to developing bond

1. Clean, sound substrate.
2. Roughened profile of substrate for mechanical interlock.
3. Open pore structure in substrate.
4. Repair material/bonding agent with sufficient paste for absorption into substrate pores.
5. Repair material is applied with sufficient pressure to facilitate contact between the repair material and the substrate at the bond line.

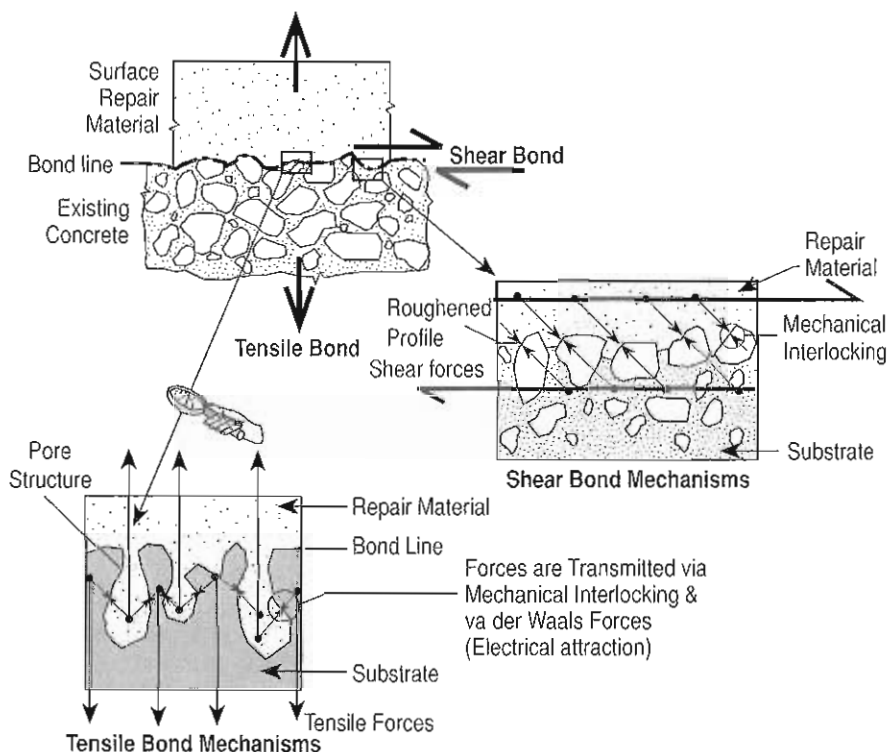
Achieving an adequate bond between repair materials and existing concrete is a critical requirement for durable surface repairs. Various techniques are available to achieve the required bond. This section presents a brief review of some of the test methods for determining the bond of repair or overlay materials to existing concrete, and a description of the step by step process of achieving an adequate bond.

The bond at the interface between the repair material and concrete substrate is likely to be subject to considerable stress from volume changes, freeze-thaw, force of gravity, and sometimes, impact and vibration. The stress states that develop at the bond lines will vary considerably, depending on the type and use of the structure. For example, the bond on the bridge deck overlay may be subject to shear stress in conjunction with tensile or compressive stress induced by shrinkage or thermal effects, and to compression and shear from service loads.¹

It is essential that the repair material achieve a strong bond to the substrate and that subsequent stresses are not sufficiently great as to cause debonding. Repairs which have bond lines in direct tension have the greatest dependency on bonding.

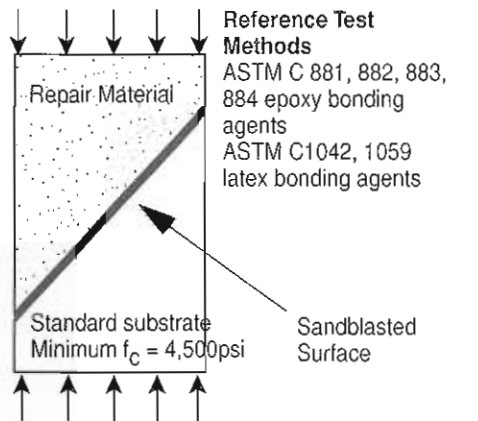
Repairs that are subject to shear stresses at the bond line are capable of stress resistance not only by bonding mechanisms, but also by aggregate interlock mechanism, which add greatly to shear bond capacity.

It should be remembered that high initial bond strength is generally not as important as bond durability.



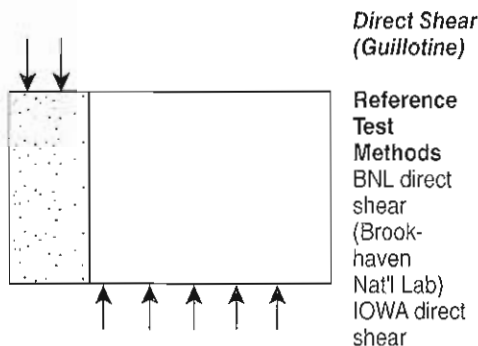
¹Wall, J.S., and Shrive, N.G., Factors Affecting Bond Between New and Old Concrete, ACI Materials Journal, Mar.-Apr. 1988, pp. 117-125.

Measuring Bond Strength



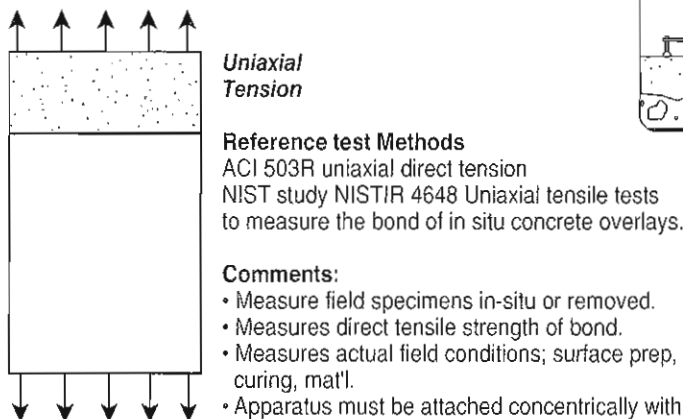
Comments:

- Laboratory test only.
- Measures materials only.
- Value affected by compressive strength of materials*.
- Value affected by degree of sandblasting*.
- *Not controlled by test method.



Comments:

- Can measure both laboratory and field specimens.
- Value affected by compressive strength of materials.
- Value affected by degree and method of surface prep.
- Measures shear bond.



Evaluation of the bond between the repair material and substrate is important in assessing the quality of the repair. In recent years, various test methods have been developed and are available at this time. Some of these methods are used extensively, while others have had little use in the field. Understanding the limitations in the reliability or applicability of each test method is critically important in achieving the performance goals.

A brief review of some of the test methods currently in use is presented below.

Slant shear test is used by most manufacturers of repair materials to evaluate product performance. The test is economical and is easily reproduced. Bond values are determined by taking the load at failure divided by the elliptical bond area. The results are highly variable depending upon the compressive strength and degree of sandblasting used. Slant shear bond values are difficult to correlate with field performance.

The method used for assessing repair materials, the slant shear test, is far from being representative of the actual in situ conditions. When the results of other test methods are compared with those obtained from the slant shear test, it is evident that the latter can give rise to inaccurate conclusions. Bond strength values are generally higher when evaluated by the slant shear method or by the direct shear method, as compared to the direct tension method.¹

¹Knab, L.I., Sprinkel, M.M., and Lane, O.J., Preliminary Performance Criteria for the Bond of Portland Cement and Latex Modified Concrete Overlays, NISTIR 89-4156, National Institute of Standards and Technology, 1989.

Direct shear method measures shear bond between the repair material and the substrate. Field and laboratory core specimens are tested in a special guillotine apparatus. Shear bond values are determined by taking the load at failure divided by the bond area. Correlations can be developed between laboratory and field tests.

Uniaxial tensile test measures the tensile bond or tensile strength of surface repairs and overlays. Direct tension bond testing establishes the location of the weakest link of the composite. Uniaxial testing can be performed in situ or in a laboratory. In situ testing is performed by coring through the repair material into the

substrate. While the core remains connected to the substrate, a tensioning device is connected to the core and loaded until failure occurs. Tensile values are determined by taking the load at failure divided by the cross sectional area of the core. The advantage of in situ testing is the benefit of evaluating actual repairs, providing feedback directly to the parties involved, establishing acceptance or necessary adjustments to the repair procedures.

Evaluating Bond Strength

Table 1. Preliminary Performance Criteria for Portland Cement Concrete (PCC) and Latex Modified Concrete (LMC) Overlay Materials Based on the BNL (Brookhaven National Laboratory) Direct Shear Bond Test Method^{1*}

Class	Overlay Material	Minimum Bond Strength (psi/MPa)*	Average Bond Strength (psi/MPa)*	Minimum Compressive Strength of Overlay psi/(MPa)*	Compressive Strength of Base Concrete psi/(MPa)*
1	LMC/PCC	200/1.4	325/2.2	$\frac{3000}{20.7}$	$\frac{3000-3500}{20.7-24.1}$
2	LMC/PCC	230/1.6	375/2.6	$\frac{3750/4000}{25.9/27.6}$	$\frac{\geq 3000}{> 20.7}$
3	LMC/PCC	260/1.8	425/2.9	$\frac{4250/5000}{29.3/34.5}$	$\frac{\geq 4000}{> 27.6}$

*The metric conversion is produced by the author.

Table 2. Relationship Between Bond Test Methods* (Adapted from Table B1¹)

Conditions	Bond Test Method	Bond Strength (psi/MPa)** Avg. of 7-10 Tests	Relationship Between Test Methods
Sandblasted, 2 day PCC overlay on 50 day old PCC	Slant shear	1190/8.2	360%
	Direct shear BNL	330/2.3	100%
	Uniaxial tension	189/1.3	57%

*The relationship between test methods is not well defined except in general. The purpose of utilizing the test data gathered in the NIST study to compare test methods is that the data represents a unique study which has compared test methods under controlled and relatively consistent conditions.

**The metric conversion is produced by the author.

¹Knab, L.I., Sprinkel, M.M., and Lane, O.J., Preliminary Performance Criteria for the Bond of Portland Cement and Latex Modified Concrete Overlays, NISTIR 89-4156, National Institute of Standards and Technology, 1989. (Order #PB90-204520 NIST).

Acceptable bond values for materials and in situ repairs are not established. Table 1 presents the range of acceptable bond properties. It is strongly recommended that the entire referenced report be read when using the preliminary performance criteria table. The values are derived from direct shear tests and are not comparable to uniaxial tensile bond test results that are generally lower as demonstrated in Table 2.

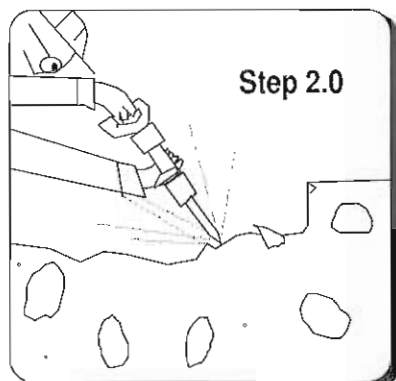
Acceptable bond values, when using the uniaxial in situ test method, are not established. The uniaxial in situ test can be used to establish general acceptance criteria for surface repair. Quantitative test results are highly dependent upon:

1. Compressive and tensile strength of substrate concrete
2. Surface preparation
3. Placement techniques
4. Repair material

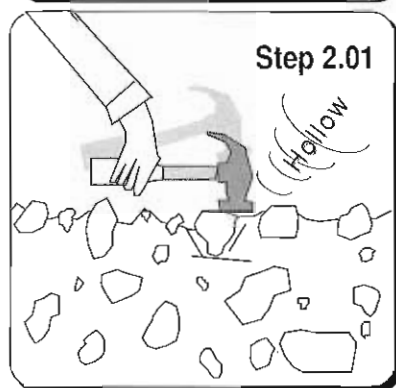
When bond strength values evaluated by this method are inadequate, adjustments to surface preparation methods and placement techniques can be made, and adequate bond achieved. By evaluating the location of the break in composite structures, the decision can be made as to whether changes in procedures or materials are necessary. The following examples demonstrate how in situ testing is used:

- Hydrodemolition techniques are used to remove concrete from a parking or bridge deck. Cleaning the slurry is time consuming and a tedious operation. By in situ tension testing, the degree of cleaning can be optimized.
- Removal of concrete by some techniques may cause damage to underlying concrete surface. By using in situ tension testing, the acceptable techniques can be selected.
- Final surface cleaning techniques may provide different degrees of bruising, profile, and pore cleaning. By in situ tension testing, various cleaning techniques can be optimized, i.e., milling without abrasive blasting vs. milling with abrasive blasting; abrasive blasting vs. high pressure water blasting.
- The effectiveness of different bonding agents can also be evaluated by these tests.

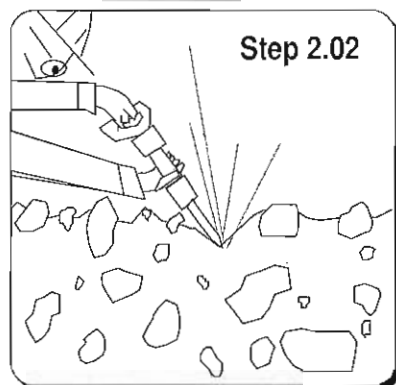
General Procedures



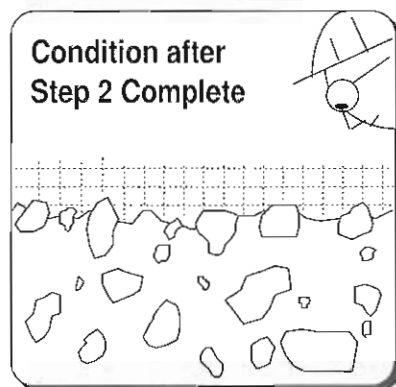
Step 2.0



Step 2.01



Step 2.02



**Condition after
Step 2 Complete**

Step 2 General

Existing concrete surfaces need to be roughened to a profile necessary to achieve mechanical interlock. The necessary profile (distance between high points and low points over a specified distance between the points) is a function of the magnitude of shear forces that will be acting, the repair material properties, the existing concrete properties, the placement technique or any combination of these. Field testing is required to establish the optimum profile.

Typical Tools Used for Development of Profile

Tool	Profile
Hand chipper	1/2" (13mm) +
Hydro milling	1/2" (13mm) +
Rotary milling	1/8"-1/4" (3-6mm)
Scabblers	1/8" (3mm) -
Shotblasters	1/8" (3mm) -
Abrasive blasting	1/8" (3mm)

A standard practice of preparing existing concrete bridge decks for overlays is rotary milling followed by abrasive blast cleaning. Excellent results are achieved with profiles less than 1/4".

Step 2.0

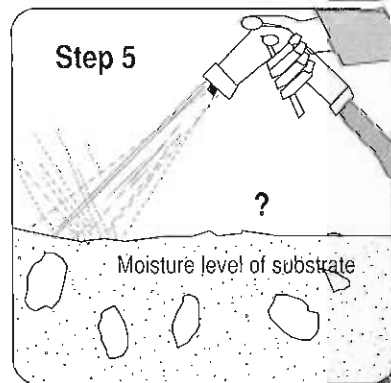
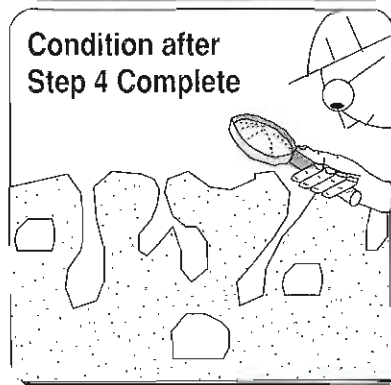
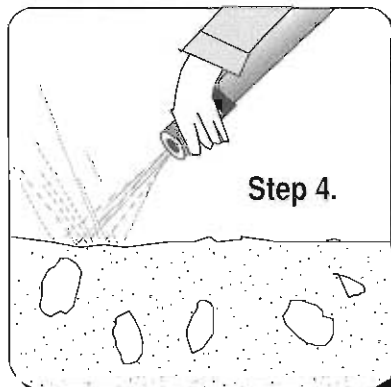
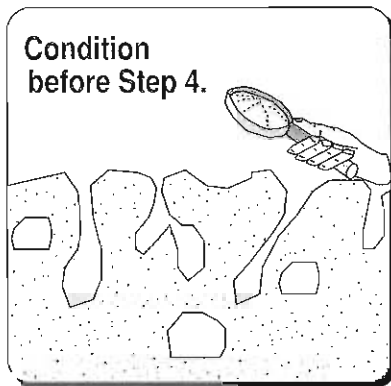
Surfaces of existing concrete expected to receive the repair material must be sound, clean, and free of bond inhibiting materials (oil, fats, hardened epoxy, etc.). An ideal sound surface is one of adequate compressive strength, free of any defects, with aggregate bonded to the cement matrix.

Step 2.01

After initial removals, surfaces should be sounded for delaminations and voids.

Step 2.02

Any concrete areas found to be unsound should be re-chipped.



Step 4 General

The surfaces of existing concrete must have an open pore structure. The absorption of the repair material into the substrate's pore structure is a critical bonding mechanism. If the

pore structure is clogged with dust, slurry or water, the absorption process will be hindered, and bond strengths reduced.

Step 4

Desirable results in opening the pore structure can be achieved using one of the following methods:

- Shotblasting (horizontal surfaces)
- Abrasive blasting
- Hydroblasting
- Combinations of abrasives and water
- Vacuum

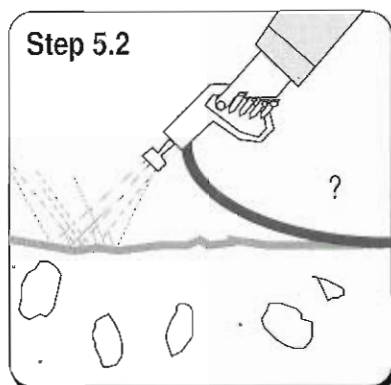
The open pore structure will provide capillary suction of the repair material, or bonding agents, into the substrate concrete. Before application of the repair materials, surfaces should be inspected for any foreign materials which might inhibit the bond.

Step 5

The moisture level of the substrate may be critical to achieving bond. An excessively dry substrate may absorb too much water from the repair material. This will result in excessive shrinkage. Excessive moisture in the substrate may clog the pores and prevent absorption of the repair mate-

rial. In situ tension testing to evaluate the optimum moisture condition for a particular substrate and repair material may be appropriate. Saturated, surface dry condition can be considered to be the best solution, unless otherwise determined.

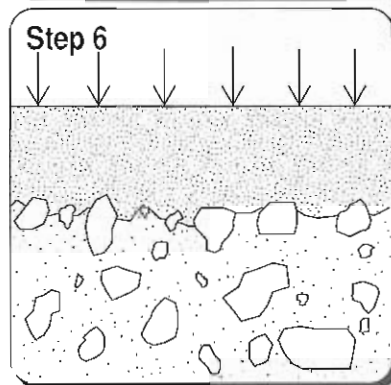
General Procedures



Step 5.2

The repair material must contain a sufficient amount of fluid paste for absorption into the open pore structure of the substrate. In some cases, a separate bonding agent is used. The

bonding agent must be easily absorbed into the pore structure and must be compatible with the repair material and substrate.

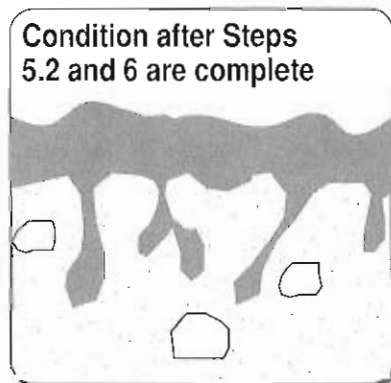


Step 6

The surface repair material should be installed in a manner which produces intimate contact between the new and the old at the bond line. Intimate contact is produced by a number of mechanisms, including:

- Internal vibration (produces fluid flow, hydraulic pressure and dissipates air pockets).

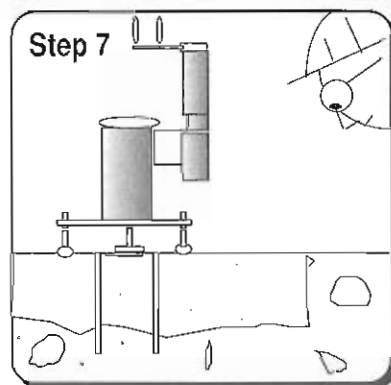
- Internal hydraulic pressure (created by pump pressure in confined spaces, utilizing form and pump or grouted preplaced aggregate repair techniques).
- High velocity impact (created by the thrusting of repair material on the prepared surface, utilizing pneumatically placed mortar).
- Low velocity impact (created by the compaction of repair material by rodding and tamping, utilizing hand applied or dry pack technique).



Step 7

Making sure that all necessary steps for achieving adequate bonding are taken, a pull-off test can be performed to monitor the tensile bond strength between repair and substrate. This in situ test involves the use of partial coring down through the repair mate-

rial and into the substrate. The method is more qualitative than quantitative. Ideally, the bond strength should be such that the composite structure should behave monolithically under load; the failure should occur in original concrete substrate.



Bonding Agents

Adequate bonding can be achieved by placing repair material directly against properly prepared substrate. There are special conditions when bonding agents are used. Three main types of bonding agents are frequently used: cement-based slurries, epoxies, and latex emulsions.

For Portland cement based repairs and overlays, cement or sand-cement slurry is used. After the substrate has been prepared, and immediately before placing the repair material, a thin coating of "creamy" grout must be vigorously and thoroughly broomed or brushed into the prepared surface.

In the case of latex-modified or microsilica-modified repair materials or overlays, the bonding grout can be broomed in from the mix itself. For latex-modified material, it can also be mixed separately. There are, now available, factory blended latex-modified cement slurry bonding agents which are mixed with water on site and applied to the prepared concrete surface.

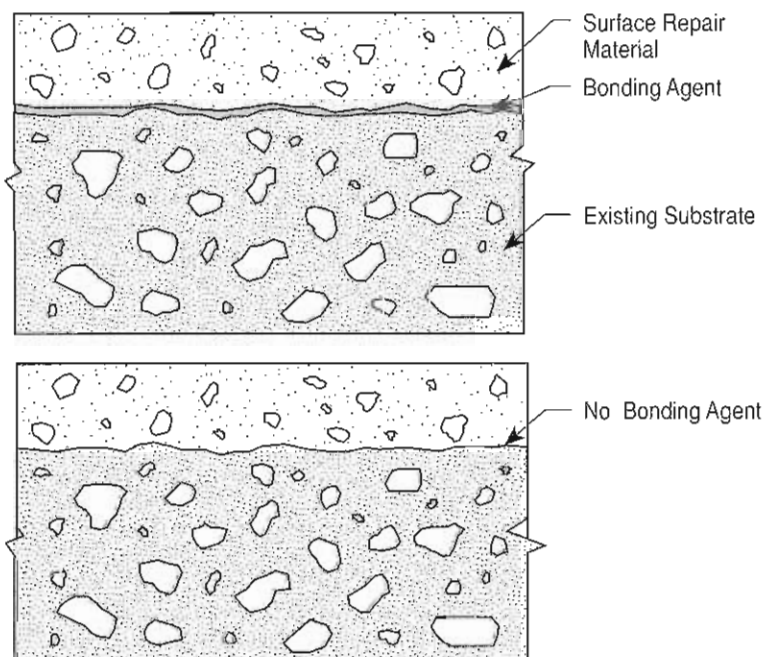
Latex bonding agents are also used in the industry. The material must meet the requirements of ASTM C 1059. Manufacturers' instructions should be strictly followed when using latex products because not all are compatible with concrete. The following latex products are used as bonding agents:

- Styrene Butadiene (SBR)
- Acrylic
- Polyvinylacetate (PVA)

Re-emulsifiable Polyvinylacetate (PVA) bonding agents should not be used in structural applications. This agent can re-emulsify after being subject to wet-dry cycles, resulting in eventual loss of bond.

A variety of epoxy products are available for use as bonding compounds. The material must meet the requirements of ASTM C 881—"Epoxy-Resin Based Bonding Systems for Concrete," related to physical properties such as bond strength, viscosity, thermal compatibility, and shrinkage. Use of an epoxy bonding agent may produce a vapor barrier, resulting in the failure of the bond. Epoxies have poor creep properties and should be avoided when the repair is subject to constant loading.

The additional step in the repair process, application of a bonding agent, may create an additional quality assurance problem. Bonding agents are not designed to compensate for poor surface preparation. Successful use of bonding agents must include the seven-step bonding process outlined above.



Additional Sources of Information

ACI 503R-89, Use of Epoxy Compounds with Concrete, ACI Manual of Concrete Practice.

Guide Specifications for Concrete Overlays for Pavements and Bridge Decks, AASHTO-AGC-ARTBA, Task Force 30 Report.

Section 7:

Placement Methods

The following topics are covered in this section:

Introduction to Placement Methods

Summary of Methods

Dry Packing

Form and Cast in Place

Form and Pump

Grouted Preplaced Aggregate

Full Depth Repair

Dry Mix Shotcrete

Wet Mix Shotcrete

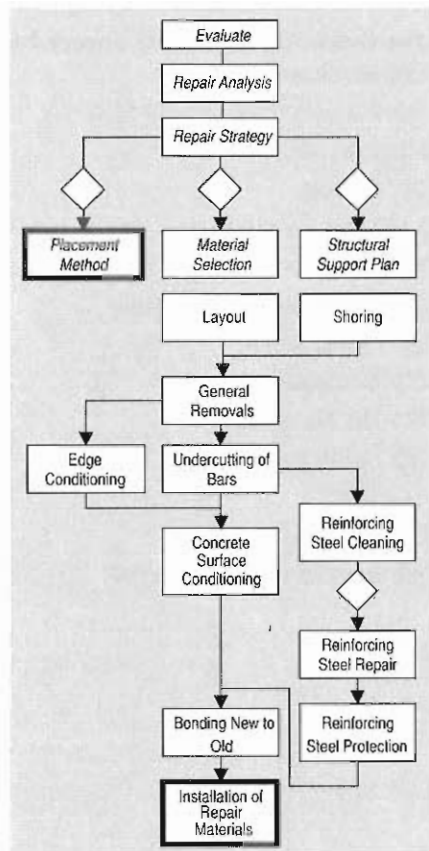
Full Depth Repair

Overlays

Hand-Applied

Summary of Overlay Materials

Introduction to Placement Methods



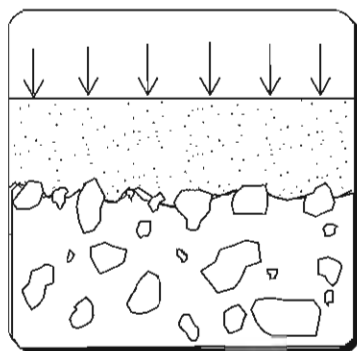
Selection of a surface repair placement method includes the following important steps:

1. Selection of a repair material that best reconstitutes the strength, integrity and performance required by the structure's original design and current situation.
2. Selection of a method of placement that will successfully deliver the repair material onto the prepared concrete substrate.
3. Checking the constructibility of the selected repair material and installation method.
4. Adjusting the material and installation methods to provide a constructible repair.

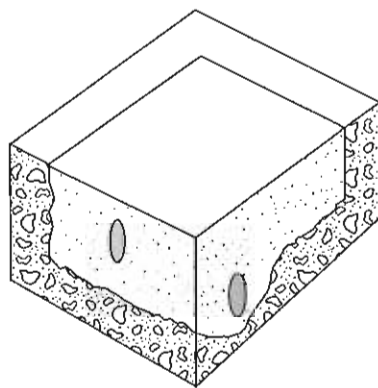
Important Considerations

The placement technique must deliver the selected repair material to the prepared substrate with specified results. The repair material must achieve satisfactory bond to the existing substrate, must fill the prepared cavity without segregation, and fully encapsulate exposed reinforcing steel. Without achieving the above requirements, the surface repair may not perform its intended structural, protective, and aesthetic duties.

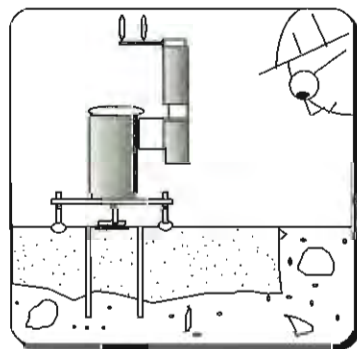
Bond of the repair to the substrate depends to a large degree on mechanical interlocking with the prepared concrete surface. For this to occur, an adequate force should be applied to the repair material to bring it into intimate contact with the prepared surface. The repair material must also have an adequate amount of binder to interact with the prepared surface. The way in which force is applied to the repair material to achieve bond depends on the application technique. In trowel-applied systems, the repair material is forced into the prepared surface by the trowel pressure applied by the finisher/cement mason.



The placement method must consolidate the repair material and create intimate contact between the repair material and the substrate.



The placement method must also fully encapsulate any exposed reinforcing steel and produce a uniform cross section without segregation, cold joints, or voids.



1. Drill core through repair into substrate.
2. Attach uni-axial tension testing device to the core.
3. Observe location of break, measure tensile strength of composite.

Dry pack techniques use pressure created when the rodding tools pound the dry pack material against the substrate. When using cast-in-place methods, the pressure is applied by internal vibration or hydraulic pressure induced by the concrete/grout pump. Pneumatically placed repair materials are propelled against the prepared surfaces, resulting in the necessary intimate contact.

The requirement for the repair material to remain uniform during placement is very important. Any segregation of repair material components will alter the repair material's physical properties. Segregation can occur during mixing when adequate time is not allowed to disperse all components. The result is high filler and low binder or high binder and low filler content. Segregation can also occur when pneumatically placed dry mix repair material is used. Air turbulence around large or clustered reinforcing steel can cause segregation, sand pockets and voids.

Complete filling of the surface cavity is also an important step. With certain placement techniques, complete filling may not occur. The form and pump or preplaced aggregate methods are susceptible to incomplete filling. Both methods use formwork which hides the filling process. To ensure proper installation, qualification of techniques and materials is recommended for most applications.

Engineering and durability aspects are the most important considerations when selecting the repair material and application method. The ultimate long-term properties of the repair material are far more important than the ease of application. Before finalizing the repair material and installation procedure, check the constructibility.

Constructibility

Constructibility is defined by these questions: Can the repair be built within the constraints specified by the engineer and the owner? Will the necessary equipment be accessible to the repair area? Will the specified installation technique allow the repaired structure to be placed in service within the time specified? Is the working environment conducive to a particular installation technique? Are there experienced contractors available for the project?

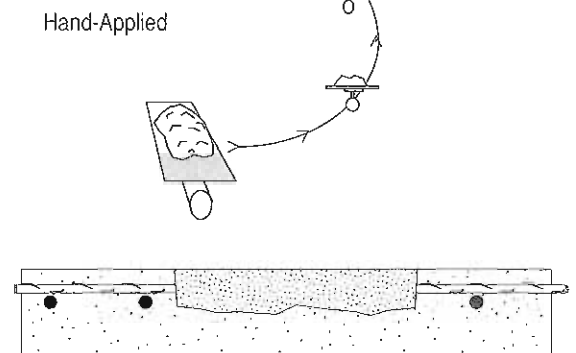
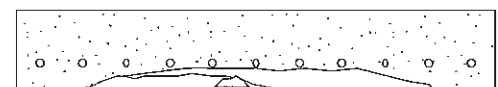
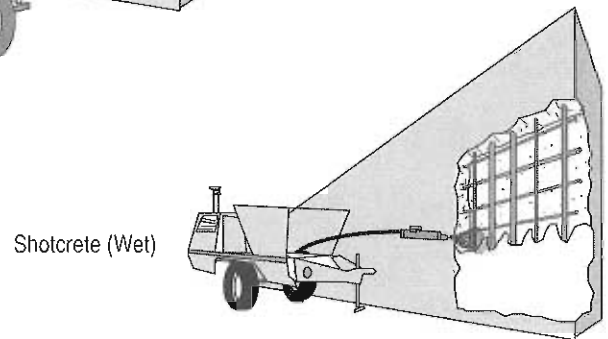
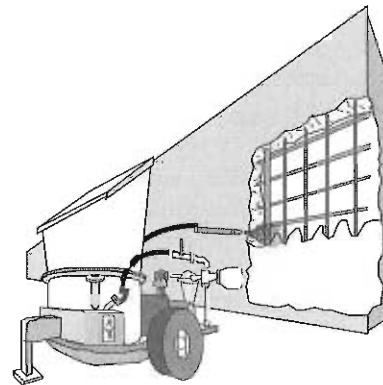
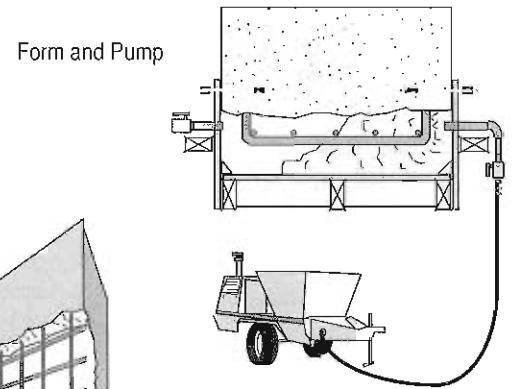
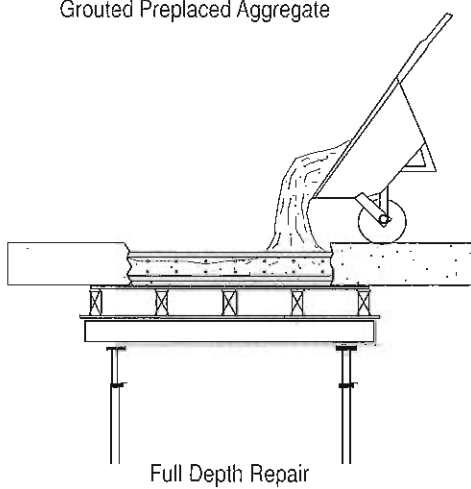
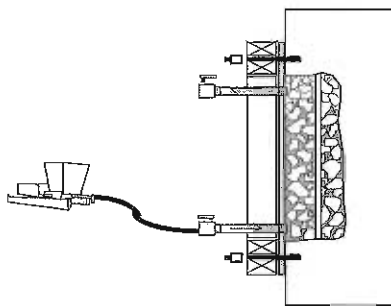
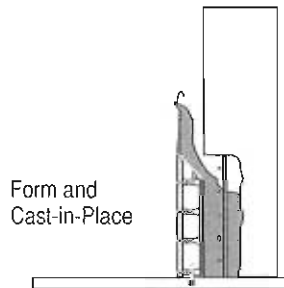
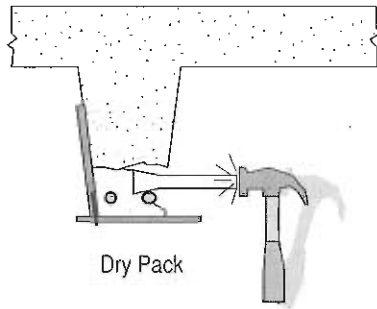
If the answers to these questions are "maybe" or "no," then the repair material and installation method need to be reassessed.

Quality Assurance and Control

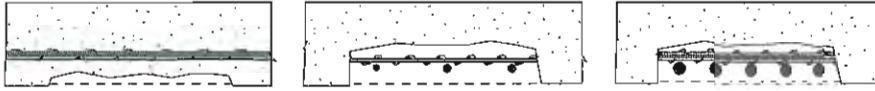
The combination of working conditions, existing concrete, structural design, and repair material is unique to every job. Many problems can arise unless proper quality assurance and routine quality control are exercised. Start by selecting a qualified contractor who has to demonstrate long-term, successful repair jobs performed with the intended installation method. If any questions exist regarding the contractor's qualifications, the repair material, or the installation technique, consider a pilot project. During the repair project, develop routine feedback as to the engineering requirements. Physical properties can be verified by sampling and testing. Bond strengths can be verified by coring through the repair and into the substrate, followed by applying a tensile force to the core.

Summary of Methods

Summary



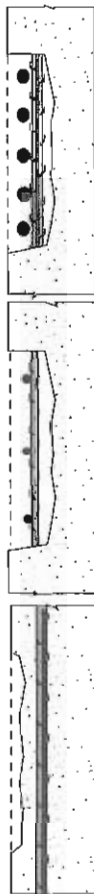
Overhead surfaces



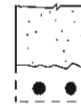
Surfaces incorporating closely spaced bars ($> \#6$), are best repaired by the form-and-pump technique. Use of other methods may result in poor consolidation around the reinforcing steel. On vertical surfaces, any of the formed methods can be used.

Small, deep repairs are best accomplished with dry packing techniques.

Thin surface repairs, which do not incorporate reinforcement, are best accomplished with hand-placed mortar or dry or wet mix shotcrete. For very thin (less than $1/4"$ (6.5mm)) or very small areas, hand placement works well. For large areas, shotcrete is the best choice. A combination of wet mix low pressure shotcrete and hand troweling are ideal techniques for resurfacing exposed aggregate or bug hole surfaces.

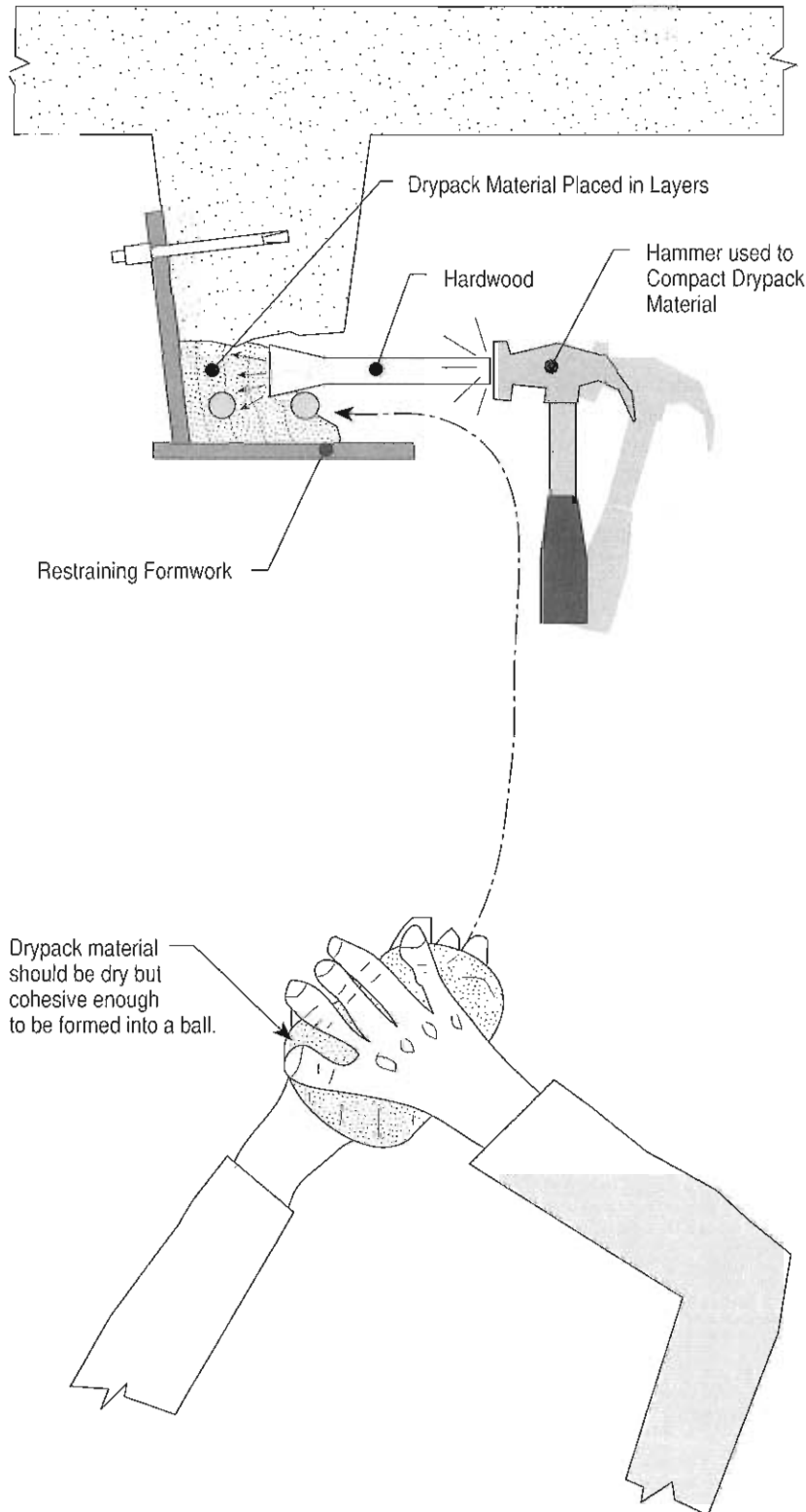


For vertical surfaces involving small bars, form-and-pump, form and cast-in-place, grouted preplaced aggregate, or shotcrete methods are the best choices. Formed methods may provide for more uniform surface appearance.



Surfaces incorporating small diameter bars ($\#6$ and less) and not congested reinforcing, can be repaired with either the form-and-pump or shotcrete techniques. When using shotcrete, care must be exercised not to form sand pockets or voids on the backside of the reinforcement.

Dry Packing



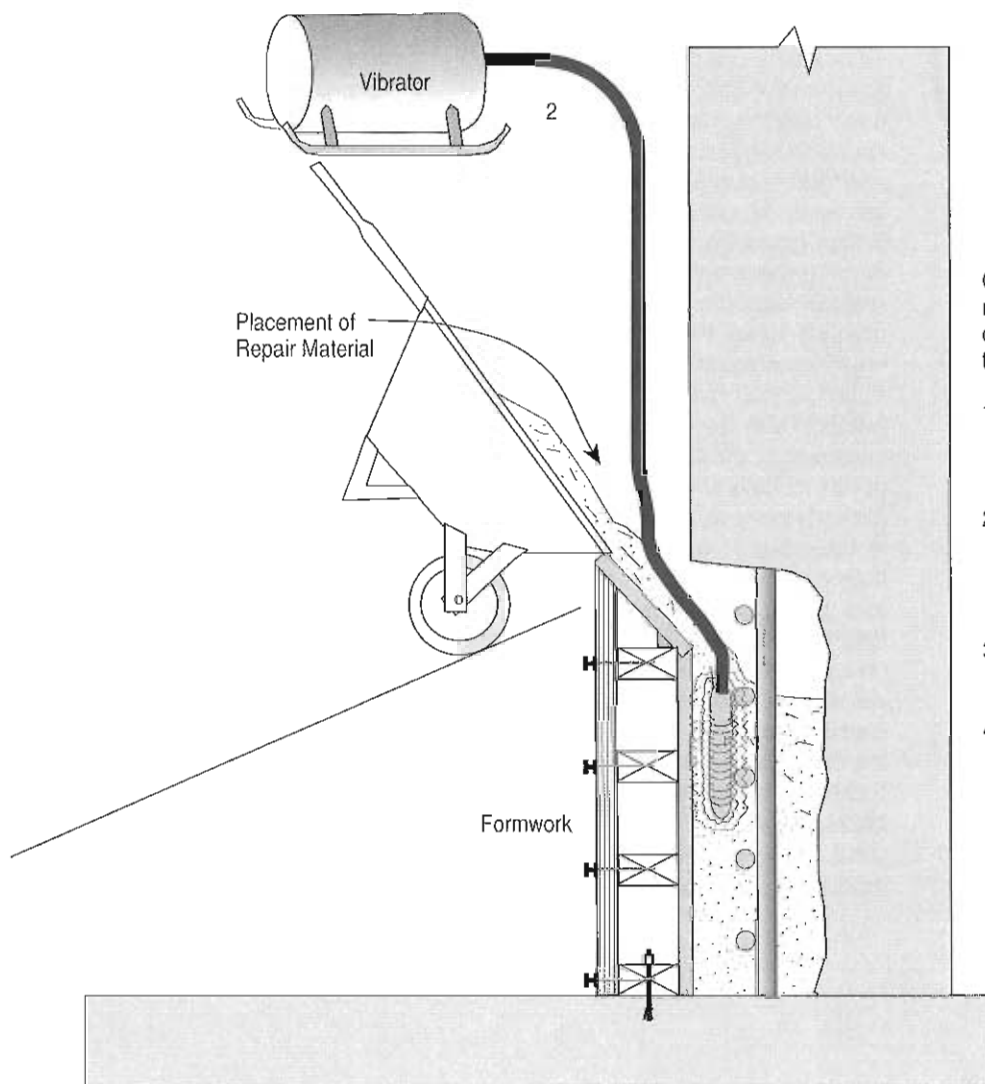
Dry packing is a method of placing zero-slump, or near zero-slump, mortar or concrete, by ramming, into surface cavities. The consistency of dry pack mortar must be such that it can be molded into a ball without excessive bleeding. Compaction densifies the mortar and provides the necessary intimate contact with the existing concrete for achieving bond. Dry packing techniques can be used in all locations: overhead, vertical and flat. Best applications are generally small cavities such as tie holes, small areas of surface honeycomb, or rib bottoms (shown in illustration).

Each dry pack mortar repair is placed in layers. Compaction is achieved with a hardwood stick to prevent polishing of the surface. Curing is accomplished with a continuous 7-day moist cure.

Form and Cast-in-Place

One of the most common methods of surface repair of vertical and, in some cases, overhead locations is the placement of formwork and casting of repair material into the prepared cavity. Formwork facilitates the use of many different repair materials, selected on the basis of in-place performance vs. constructibility. The repair material must be of low shrinkage and provide the necessary flowability. Placement of repair materials follows normal placement practice. Rodding or

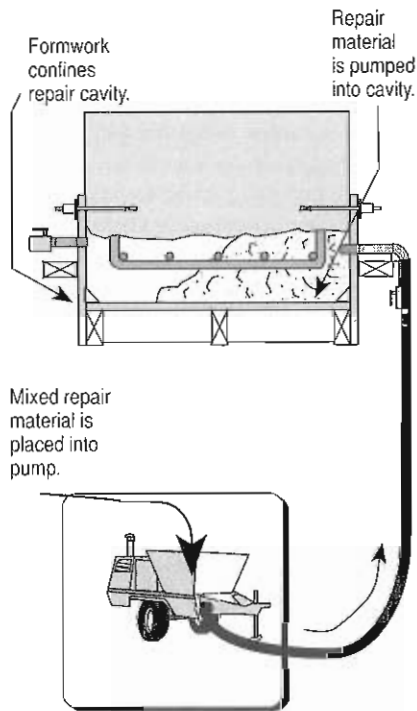
internal vibration is necessary to remove air and provide intimate contact with the existing concrete substrate. Formed surfaces make the placement of bonding agents difficult and, in most applications, unnecessary. Forms are made with necessary shoots to provide access of the repair material into the formed cavity. In some applications, complete filling of the cavity may be difficult. In those cases, a final step of dry packing the remaining cavity works well.



Consolidation of the repair material is accomplished with one of the following techniques:

1. The repair material is formulated to be extremely flowable and self-consolidating, or...
2. the repair material is placed into top of form and free falls into the prepared cavity where conventional internal vibrators are used, or...
3. rodding of the repair material from an access point in the formwork, or...
4. external vibration of formwork.

Form and Pump



There are many techniques available to restore damaged or deteriorated concrete surfaces. Each surface repair technique offers advantages and limitations, depending upon the specific conditions of the repair project. Form and pump technique is a relatively new method developed over the past 20

years, coinciding with the development of variable output concrete and mortar pumps. Form and pump technique is used for vertical and overhead applications. Form and pump technique is an alternative to shotcrete (gunite), hand placement, and grouted preplaced aggregate techniques.

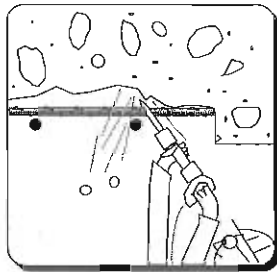
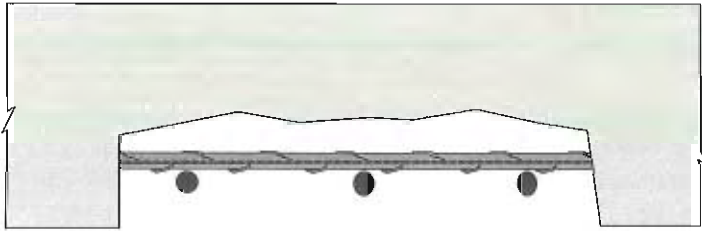
What Is the Form and Pump Technique?

The form and pump repair method is a two-step process of constructing formwork and pumping repair material into the cavity confined by formwork and existing concrete. The form and pump technique allows the use of many different repair materials. The necessary requirement for material selection is pumpability. Various pumps are used, depending upon the mix design (particularly the aggregate size). Prior to construction of formwork, any surfaces that may cause air to become trapped during the pumping process must be trimmed, or vent tubes installed. Repair materials are mixed and pumped into the confined cavity. The sequence of pumping is from low points to high points and when performed overhead, from one extremity to the other. Large areas may require bulkheading to separate placements into manageable areas. When the cavity is full, pump pressure is exerted on the form, causing the repair material to consolidate and make intimate contact, and effect bonding with existing concrete surfaces. Form and pump technique offers many advantages to alternative techniques, such as shotcrete, hand-placement, and preplaced aggregate. Advantages include:

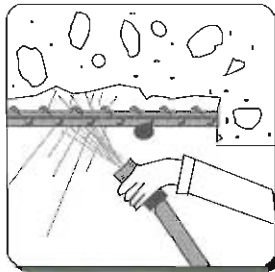
- The use of almost any repair material—from fine grained mortars to coarse aggregate concrete, including polymers and hydraulic cement materials.
- Placement is not limited by depth of repair or by size or density of exposed reinforcement.
- Repair materials are premixed and placed to provide a uniform cross section without segregation or intermediate bond lines.
- The process does not depend on fighting the forces of gravity; all materials are supported by formwork during the placement and curing process.
- The pressurization process consolidates the repair material, providing for full encapsulation of exposed reinforcing steel.
- The formwork protects the repair material during the curing process.
- The process is less subject to individual operator error.
- Quality assurance of the in-place repair is easier to provide.

Surface Preparation

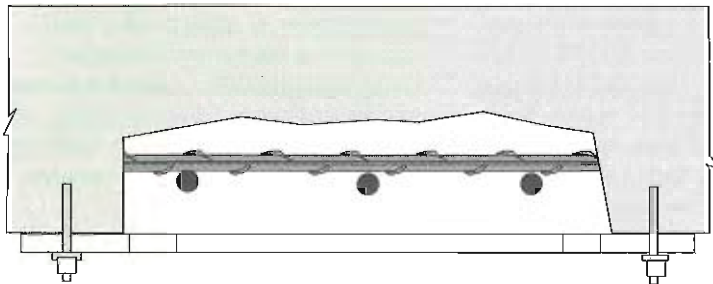
Regardless of the repair method, surface preparation is essentially the same. Concrete is removed until sound concrete is located. Exposed bars are undercut, and surfaces are cleaned with high pressure water or are abrasively blasted.



Surface preparation requires removal of loose and deteriorated concrete, and also includes concrete removal behind exposed bars.



After completion of removals and cleaning, formwork is erected to enclose cavity.

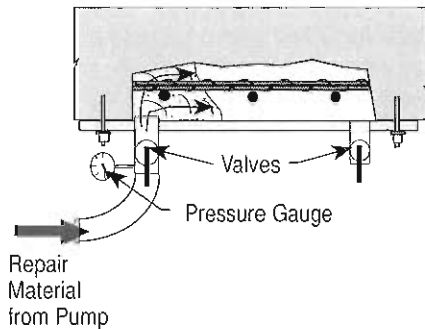


With form and pump techniques, it is important to understand how the existing surfaces will permit the repair material to penetrate and flow. Surfaces that might trap air need to be trimmed, or vent pipes may be provided in the formwork. Profile roughness from hand chipping or hydrodemolition is not generally a problem for entrapping air. Flow of the repair material (while flowing within the formed cavity) will most likely remove air from the profile.

Formwork

Formwork must accommodate the weight and pressure of the repair material. Design of the forms should follow standard practice for cast-in-place concrete construction except for the calculation of form pressure. Form pressure should be designed for a minimum of 14 psi (96.5 kPa). Maximum pressure exerted on formwork occurs after the formwork cavity is full and pressurized. Formwork is best attached directly to the concrete surface with expansion anchors or standard form ties. All anchors should be preloaded to prevent slippage during placement. In some applications shoring or scaffolding can be used to support the formwork. Forms should be constructed to fit tightly against existing concrete surfaces. Preformed foam gaskets or cast-in-place foam works well to address difficult-to-match surfaces. Attachment of pump hose to form work is achieved with various techniques including plumbing fittings with flanges and ball valves or with the use of pump line attachment with hand-held friction fit insertion followed by wooden plugs.

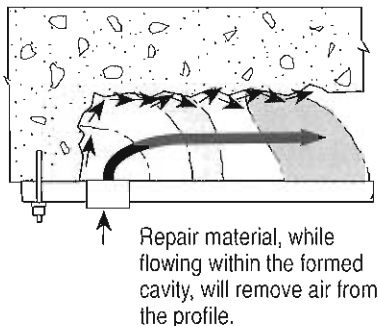
Form and Pump, continued



Pumping Equipment

Pumping equipment is generally matched to the type of repair material and the size of the repair project. The specified repair material requires pumping through a pump line to the formed cavity. Cementitious repair materials have various aggregate contents and aggregate sizes. Fine-grained repair mixes with little or no coarse

aggregate can be pumped with mono-type pumps or piston/ball valve pumps. Repair materials with large aggregates (larger than 3/8" (9.5mm)) are best pumped with hydraulic/swing valve pumps. All pumping equipment must have adequate controls to regulate flow rates.



Materials

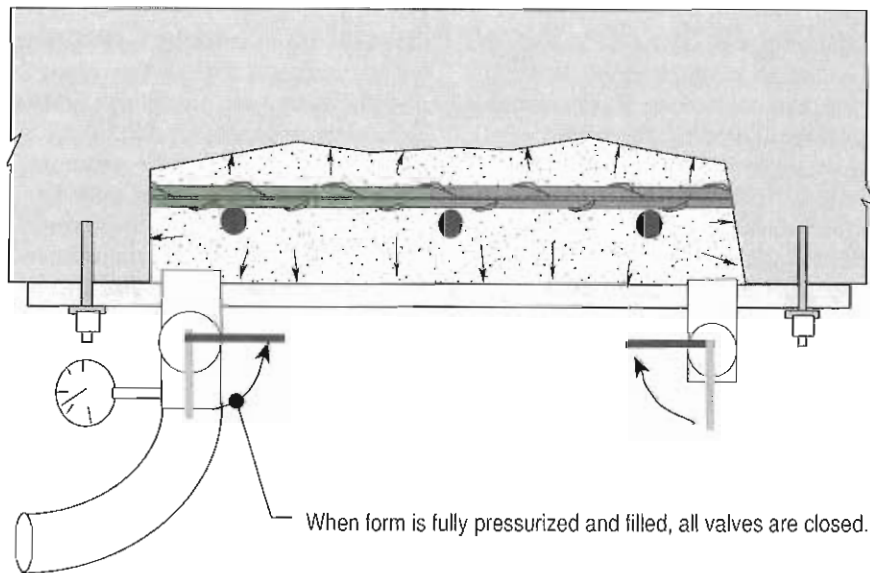
Constructibility requirements for materials used with form and pump technique are limited only by their ability to be pumped and their flow characteristics. More important than constructibility are the materials' in-place properties, such as low drying shrinkage, compatible strength, thermal and elastic properties, and any durability requirements. While constructibility of the repair materials requires good pumpability and flowability, these required characteristics should not sacrifice the requirement of low drying shrinkage. Drying shrinkage can cause cracking, delamination, inability to carry loads and low durability. Pump-

ability and flowability can be brought to the material with aggregate shape and chemical admixtures which preserve low water-cement ratio, yet provide high slump. Prepackaged repair materials, which are designed for pumping and incorporate shrinkage compensating additives, are appropriate for many applications. Materials should be screened for drying shrinkage to find those with low shrinkage. Shrinkage testing in accordance with ASTM C 157 (modified in accordance with ASTM C 928 and measured over a 120 day period) will provide meaningful shrinkage properties.

Placement

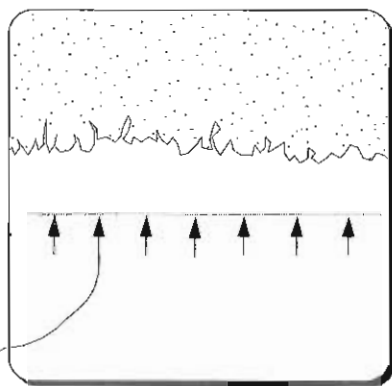
The sequence of material placement into the formed cavity depends upon the geometrics involved. Vertical surfaces start at the lowest point, filling in a manner that prevents air entrapment. Arrangement of ports for pump line attachments is usually horizontal with spacing of 3 to 4 feet (90 to 120 cm) in grid form. Pumping continues even after material flow occurs from adjacent ports in order to expel air. When the flow is without intrusion of air, the pump is temporarily shut off,

the port closed off, and the pump line connected to the adjacent port which has seen flow. The sequence is continued until the cavity is filled. In some conditions, the cavity can be pumped from one port. In this situation, each adjacent port is capped off as flow occurs. It is necessary to monitor pump line pressure to prevent excessive backpressure when pumping long distances. Once the cavity is filled, the full line pressure is available to pressurize the formed cavity.



Care must be exercised in the final pressurization, since the excessive pump line pressure (hydraulic pumps can exert in excess of 800 psi (5.5 MPa)) may cause the form to fail. In most applications pressure gauges should be attached to the pump line near the exit port to monitor cavity pressure, which should not exceed the formwork design pressure. If the formwork fails due to over-pressurization, the failure will generally occur as a slight movement in a panel seam or perimeter seal. The failure is not explosive since there is no stored energy. Overhead placements are accomplished by starting at an extremity of the surface and proceeding in a fashion similar to vertical placements. Material will flow radially from the injection port to adjacent ports. Repairs involving soffit and vertical faces of members can be combined into one placement. In this case, placement begins at the lowest elevation and follows the procedure detailed above for each orientation. Large areas of repair should be sectionalized utilizing bulkheads. Bulkheads can be constructed of repair material and left in place. Utilizing bulkheads and manageable placement volumes limits the risk of problems associated with large placements and allows pressurization to occur within shorter durations of material mixing.

Form and Pump, continued



Hydraulic pressure from pump drives repair material into pore structure of substrate.

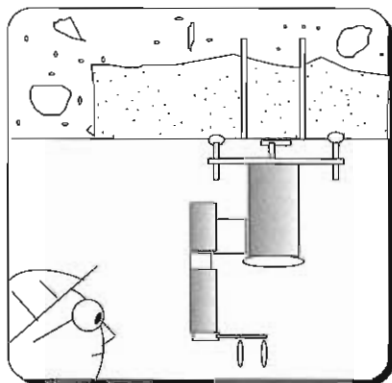
Bonding of the New Repair Material to Existing Concrete

Achieving an adequate bond between repair material and existing concrete is a critical requirement for surface repairs. To receive the repair material, surfaces of existing concrete must be sound, clean and free of bond-inhibiting materials (oil, fats, hardened epoxy, etc.). The surfaces of existing concrete must have an open pore structure.

An important bonding mechanism is the absorption of the repair material into the surface pore structure. If the pore structure is clogged with dust, slurry, or water, the absorption process

will be hindered. The surface repair material must have a sufficient amount of fluid paste for absorption into the open pore structure of the substrate. The surface repair material must be installed in a manner which produces intimate contact between the new and existing materials at the bond line.

Internal hydraulic pressure created by pump pressure in confined spaces provides additional driving force to knit the new and existing materials together. With most pumpable repair materials, separate bonding agents are not required.



Direct Uniaxial Tension Device

Quality Assurance

Any surface repair technique is subject to less than expected results. Care and understanding must be exercised to perform the various steps involved. With all techniques, each step is critical to the success of the completed repair. A perfect repair material will not compensate for imperfect surface preparation. The beginning of any repair project should include a mock-up or pilot project which tests the proposed procedure and repair material against required objectives of the project. Once the procedure and materials are deemed satisfactory, the repair project will require ongoing quality control and assurance.

Measuring uniformity, density, bond, and strength are the most common quality control procedures. Measuring in situ uniformity, density, and bond is best performed by extracting core samples which pass through the new and existing materials. Visual examination of the cores reveals uniformity and density defects. Attachment of a direct uniaxial tension pull device to

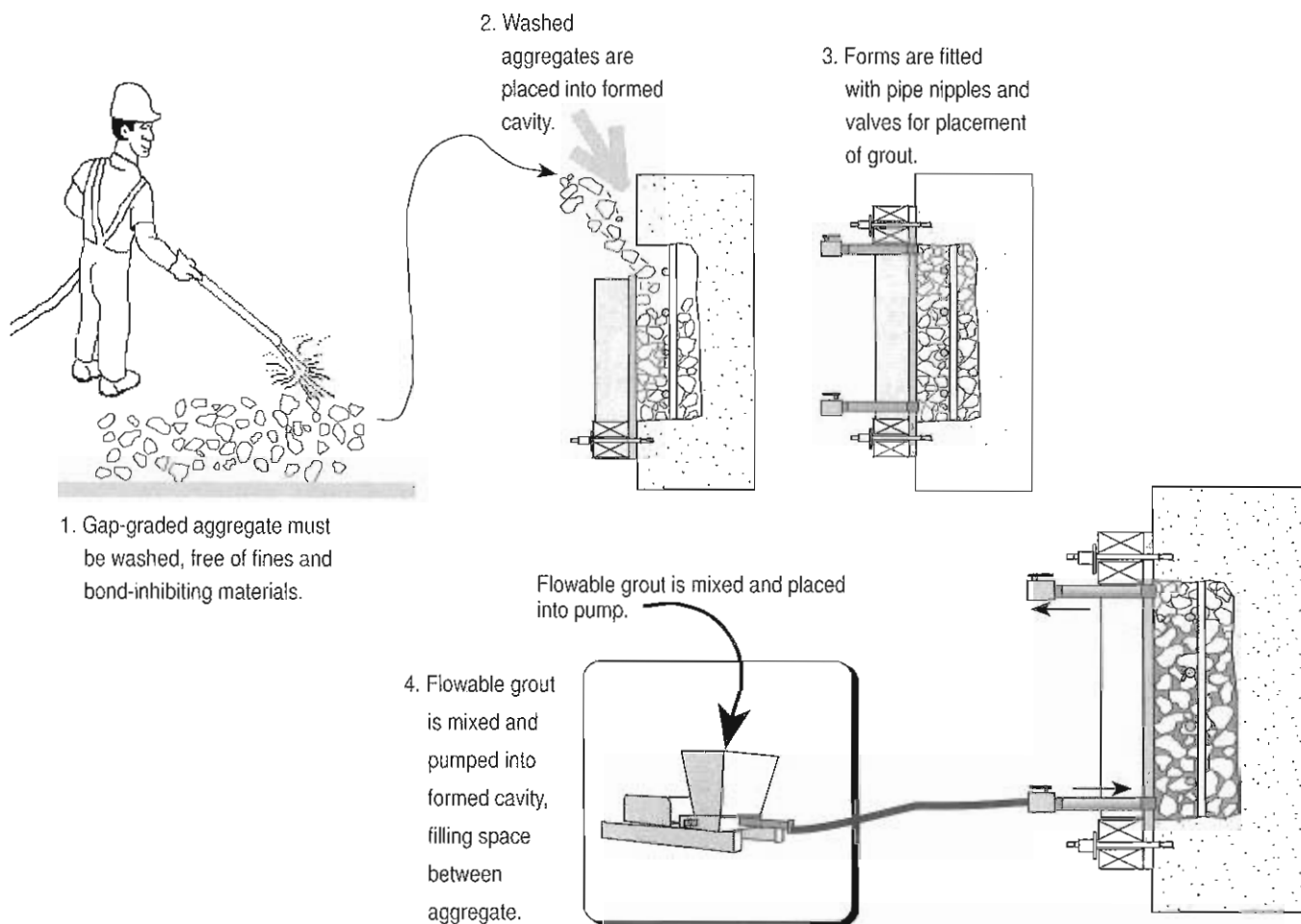
the in-place core quantitatively measures tensile stress capability of the composite material. Generally, the tension device is loaded to failure. Upon failure of the core specimen from the member, a visual examination of the failure plane location reveals whether the failure occurred at the bond line, within the substrate, or within the repair material. The most desirable location of the failure plane is within the substrate. Failures at the bond line at unacceptably low tension stress levels generally point to problems with surface preparation procedures or improper form pressurization.

The most common problem associated with form and pump repairs is lack of pressurization of the formed cavity, which may result in areas without repair material or poor bond. Upon completion of the surface repair (after formwork has been removed) surfaces should be sounded with a hammer to locate any areas that might be unbonded or contain voids.

Grouted Preplaced Aggregate

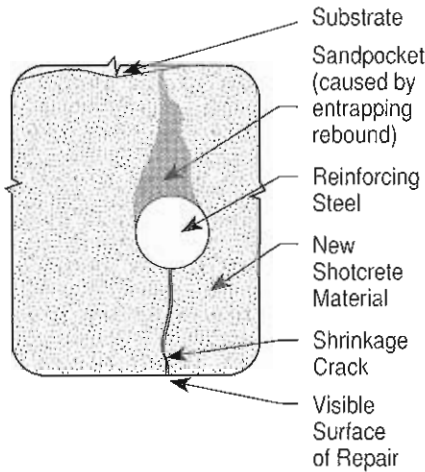
Grouted preplaced aggregate is a two-step process. The first step involves aggregate placement into the cavity during the erection of formwork. The aggregate is gap-graded and washed of all fines. The void ratio of the cavity, after the aggregate is placed, ranges from 40% to 50%. The second step involves pumping a highly flowable grout through the formwork and into the preplaced aggregate. Grout flow fills the lower voids and progressively fills the cavity, eventually flowing to higher elevation ports. After grout flows from adjacent ports, the grout hose is disconnected from the port being pumped, and reconnected

to the port showing new flow. The process continues until the cavity is full and pressurized. The grout flow makes contact with the prepared substrate as the cavity is filled, providing intimate contact and bonding. A unique advantage of this method is the low drying shrinkage of the repair material due to the point-to-point contact between the coarse aggregates. The aggregate contact restricts the volume change of the cement grout as drying shrinkage occurs. Various grouts can be used for the grouting process. Most popular are Portland cement-based grouts and, for special applications, epoxy resins.



Dry Mix Shotcrete

Enlarged View of Sandpocket
Formed Behind Reinforcing Steel

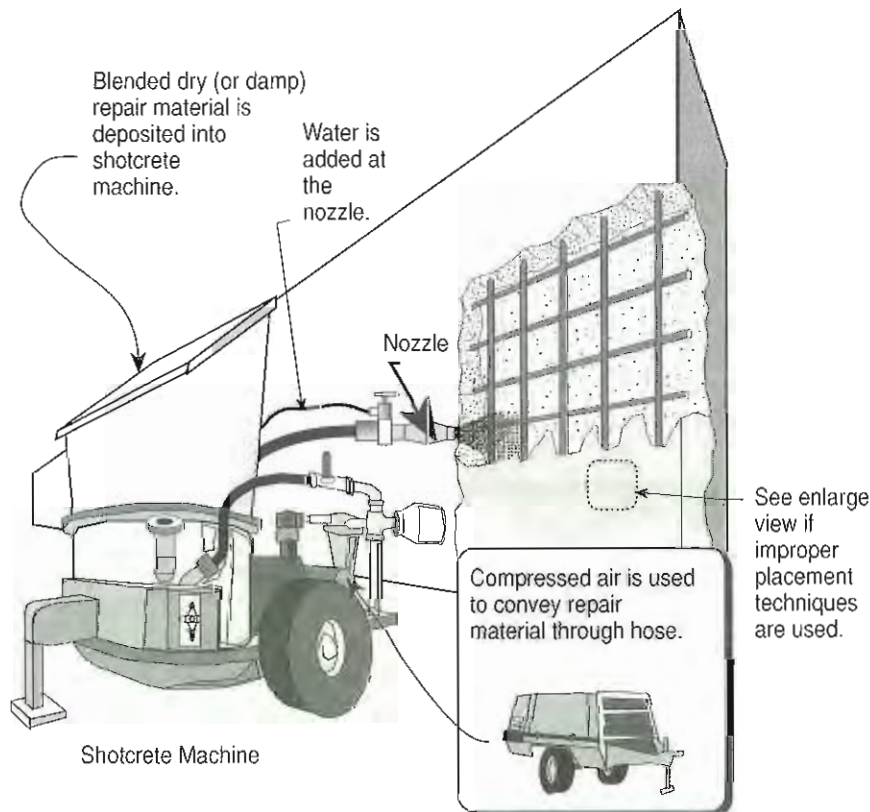


Dry mix shotcrete is a method that involves the premixing of binder and aggregates, which are then fed into a special mechanical feeder metering the premixed materials into a hose. The material is conveyed through the hose with compressed air to a nozzle which is outfitted with a water ring where additional water is mixed with the binder and aggregates. The mix is jetted from the nozzle at high velocity onto the prepared concrete surfaces. The process varies, depending upon the necessary thickness and orientation. Where the repair is thick, the process may involve the placement of multiple layers. Excessive thickness of

individual layers may result in sloughing off. The use of special admixtures has helped improve the workability and performance of shotcrete. Silica fume is a good property enhancer. It improves the concrete's adhesive and cohesive properties, along with its ability to provide for larger placement thicknesses. The resulting hardened properties include increased flexural and compressive strengths and increased durability to freeze-thaw and chemical attack. The use of chemical accelerators should be avoided where not absolutely necessary. Accelerators have been found to cause increased drying shrinkage¹.

Typical Problems Associated with Shotcrete Repairs

- Presence of voids due to encapsulated rebound; common when multiple layers are used or when heavy reinforcing is encountered.
- Shrinkage cracking caused by high cement content, improper curing, or excessive water content.



¹Morgan, D.R., Developments in Shotcrete for Repairs and Rehabilitation, Concrete Construction, No. 9, September 1991.

Additives for Dry Mix Shotcrete

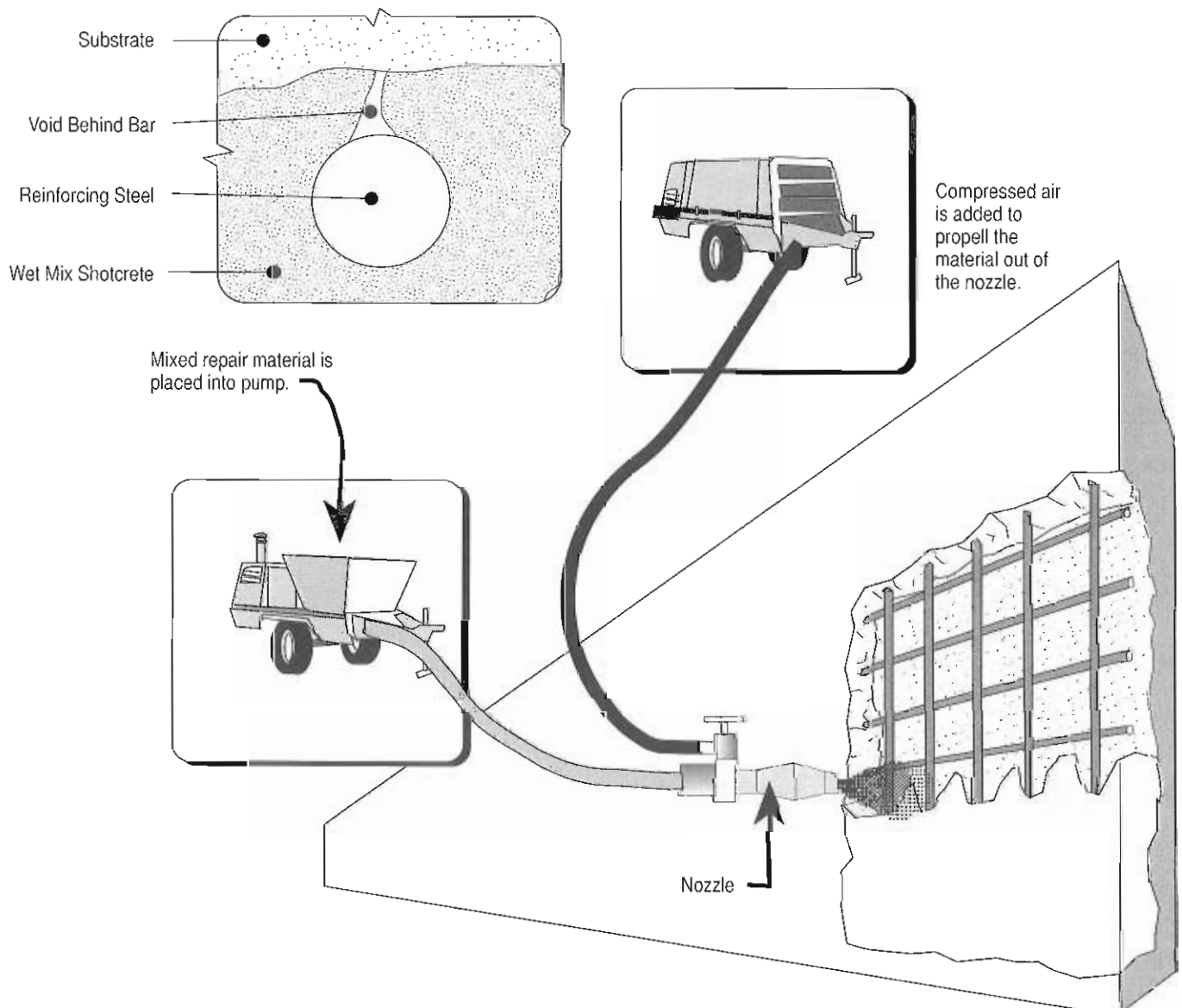
Additives	Benefit	Comments
Silica Fume	<ul style="list-style-type: none"> • Increased thickness • Increased density • Increased freeze-thaw resistance • Increased chemical resistance • Reduced rebound • Increased adhesion • Increased flexural and compressive strength 	
Accelerators	<ul style="list-style-type: none"> • Increase/buildup of layers • Reduced initial set time • Increase early strength gain 	<ul style="list-style-type: none"> • Increased drying shrinkage • Reduced shotcrete strength with age • Not necessary if silica fume is used
Steel Fiber	<ul style="list-style-type: none"> • Elimination of shadows and voids which are created with conventional reinforcement • Improved impact resistance. 	
Polypropylene Fibers	<ul style="list-style-type: none"> • Reduced plastic shrinkage cracking 	
Latex	<ul style="list-style-type: none"> • Improved flexural, tensile bond strengths • Increased resistance to freeze-thaw and chemical attack. 	<ul style="list-style-type: none"> • Latex hardened film may occur between layers, causing delamination.

Wet Mix Shotcrete

Wet mix shotcrete is a method that involves premixing of all ingredients (except accelerators) including binder, aggregates, admixtures, and mixing water. The premixed repair materials are deposited into a pump or pressure vessel which transports the materials to an exit nozzle, where compressed

air is introduced. The repair material is propelled onto the substrate with compressed air. Admixtures can be used to enhance the shotcrete material. Silica fume and fibers are commonly used to enhance durability. Air entrainment is required for freeze-thaw resistance.

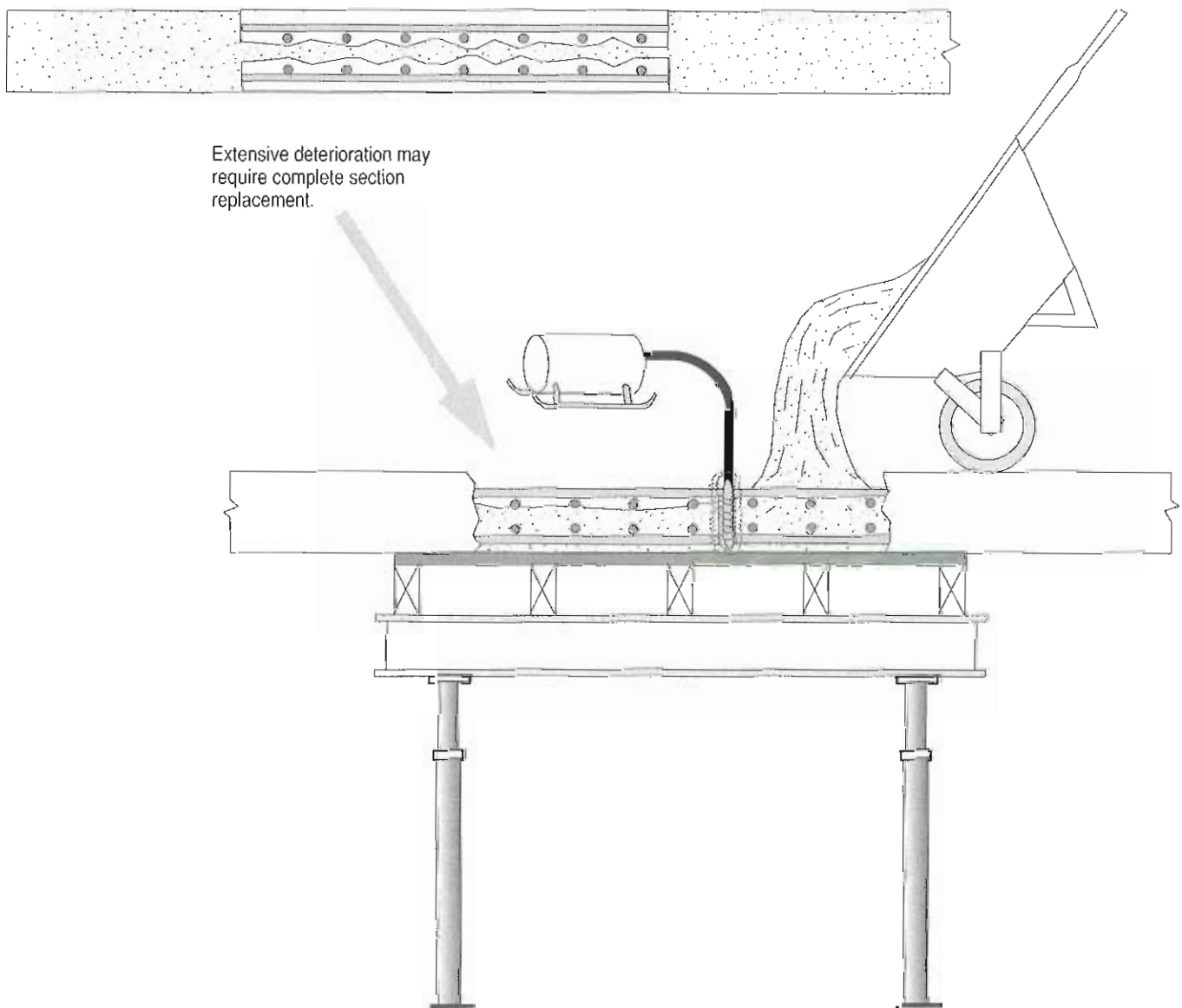
Potential Problem if Improperly Placed



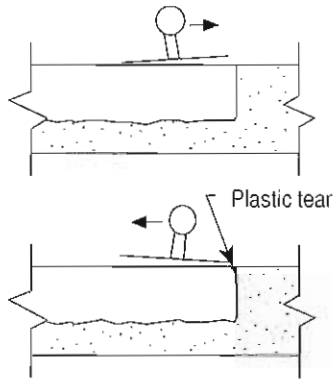
Full Depth Repair

In certain situations, surface repair may be better served by full depth repair. For example, when concrete surfaces have extensive surface damage, it may be more economical and provide for longer lasting repairs if the affected part of the member is removed and reconstructed. Consideration should be given to minimizing the restrained perimeter drying shrink-

age. After placement of the new concrete, drying shrinkage results, causing tension within the newly reconstructed member and at the bond between new and old. In most cases, if tension stresses are not addressed, unplanned cracking may result. Low shrinkage concrete mixes should be used to reduce shrinkage stresses.



Overlays



Overlays are used to repair concrete structures as a remedy for a variety of concrete problems. They may be used to improve drainage, rideability, or load carrying capacity; to increase skid resistance; or to protect underlying concrete from aggressive environments. Many overlays also address underlying surface deterioration problems. Overlays can be constructed of different materials from very thin (1/8" (3mm)) to very thick.

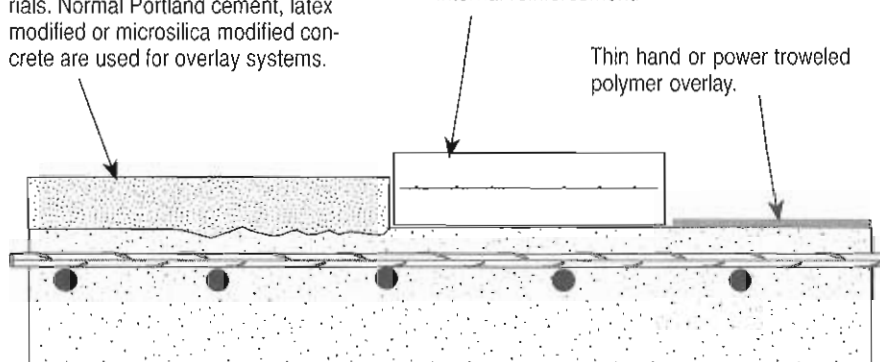
Bridge and parking decks, as well as concrete pavements, are common locations for the use of bonded overlays for restoring existing worn and deteriorated concrete. Surface preparation of existing decks utilizes milling, hydromilling, and hand chipping techniques. Common materials used in the overlays are low water/cement ratio Portland cement concrete, latex-modified Portland cement concrete, and microsilica-modified Portland cement concrete. Most bonded overlays used in parking and bridge decks and pavement repairs involve thickness ranges of 1.5" to 3" (38mm to 76mm). Many applications do not require additional reinforcement. Overlays require special attention to placement techniques to prevent various problems such as plastic shrinkage cracking, lack of consolidation, segregation, or poor bonding.

Other types of overlays involve the use of polymer and polymer-modified mortars for thin applications (less than 1/8" (3mm)). The most common polymer is epoxy, which is combined with graded sand to form a mortar. Polymers also offer additional protection from aggressive environments.

Overlays for bridges and parking structures generally include surface repairs to deteriorated areas of the deck. Hand or power screeds are used to level and consolidate the overlay materials. Normal Portland cement, latex modified or microsilica modified concrete are used for overlay systems.

Thick unbonded overlay, these require internal reinforcement.

Thin hand or power troweled polymer overlay.



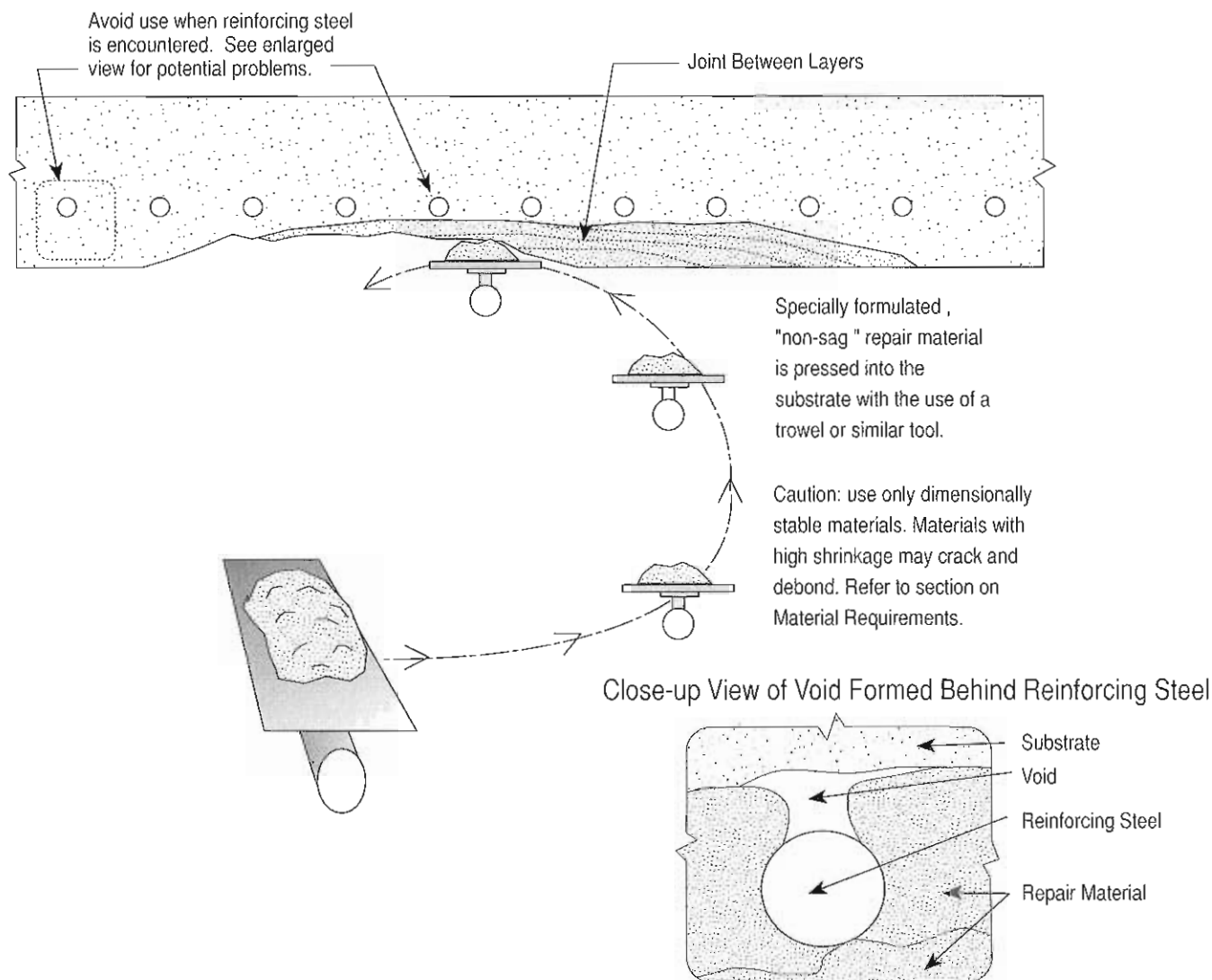
Summary of Overlay Materials

	Low Slump Dense Concrete (LSDC)	Low Water- Cement Ratio Concrete (LW/C)	Latex Modified Concrete (LMC)	Microsilica Modified Concrete (SFC)	Portland Cement Concrete Over Deck Membrane	Polymer Concrete (Epoxy, MNA, PC)	Comments
Thickness:							
0.125"–0.75"			✓			✓	
0.75"–2"			✓	✓			
2"–3"	✓	✓	✓	✓			
>3"	✓	✓	✓	✓	✓		
Performance:							
—reestablishes new grade	✓	✓	✓	✓	✓	✓	Improves drainage
—Wearing surface	✓	✓	✓	✓	✓	✓	
—Concrete and reinforcement protection	✓	✓	✓	✓	✓	✓	Minimizes penetration and diffusion of aggressive agents.
—Waterproofing the deck					✓		Including cracks and construction joints
—Placed with surface repair	✓	✓	✓	✓			
—Dead load on structure	Moderate	Moderate	Moderate	Moderate	High	Low	Strengthening of superstructure may be necessary.
—Monolithic with slab	✓	✓	✓	✓		✓	Surface of existing deck should be properly prepared for adequate bond.
Overlay Reinforcement:							
—W.W.F.	✓	✓	✓	✓	✓		
—Rebar mat					✓		
—Steel fiber	✓	✓	✓	✓			For high impact conditions
—Plastic fiber	✓	✓	✓	✓		✓	Controls plastic shrinkage
—None	✓	✓	✓	✓		✓	
Compatibility:							
—With elastic membrane	✓	✓	✓	✓			
—Penetrating sealer	✓	✓		✓	✓		

Hand-Applied

Hand-applied techniques are used to place non-sag repair materials on vertical and overhead locations. Most hand-applied materials are special blends of cement, finely graded aggregates, non-sag fillers, shrinkage compensating systems, and water. The mixed material is applied to the prepared surface with either a trowel or by hand. The applied pressure drives the repair material into the pore structure of the exposed concrete. The repair material is designed to "hang"

in place until subsequent layers are added. Each layer is roughened to promote bond with the next layer. The best use of this technique is for topical cosmetic repairs not involving reinforcing steel. When reinforcing steel is encountered, it is very difficult to consolidate and provide for complete encapsulation of the reinforcing steel. Problems associated with this technique involve poor bond between layers and voids around embedded reinforcing steel.



Additional Sources of Information

ACI 304R-39, Guide for Measuring, Mixing, Transporting and Placing Concrete.

ACI 304.2R-71 (Revised 1982), Placing Concrete by Pumping Methods.

ACI 506R-90, Guide to Shotcrete.

Guide Specifications for Concrete Overlays for Pavements and Bridge Decks, Task Force 30 Report, AASHTO-AGC-ARTBA.

Evaluation and Repair of Concrete Structures, Engineer Manual EM 1110-2-2002, U.S. Army Corps of Engineers, 1986.

American Concrete Paving Association Technical Bulletin TB-007.0-C, Guidelines For Bonded Concrete Overlay

Part Four
**Strengthening
and
Stabilization**

Part Four

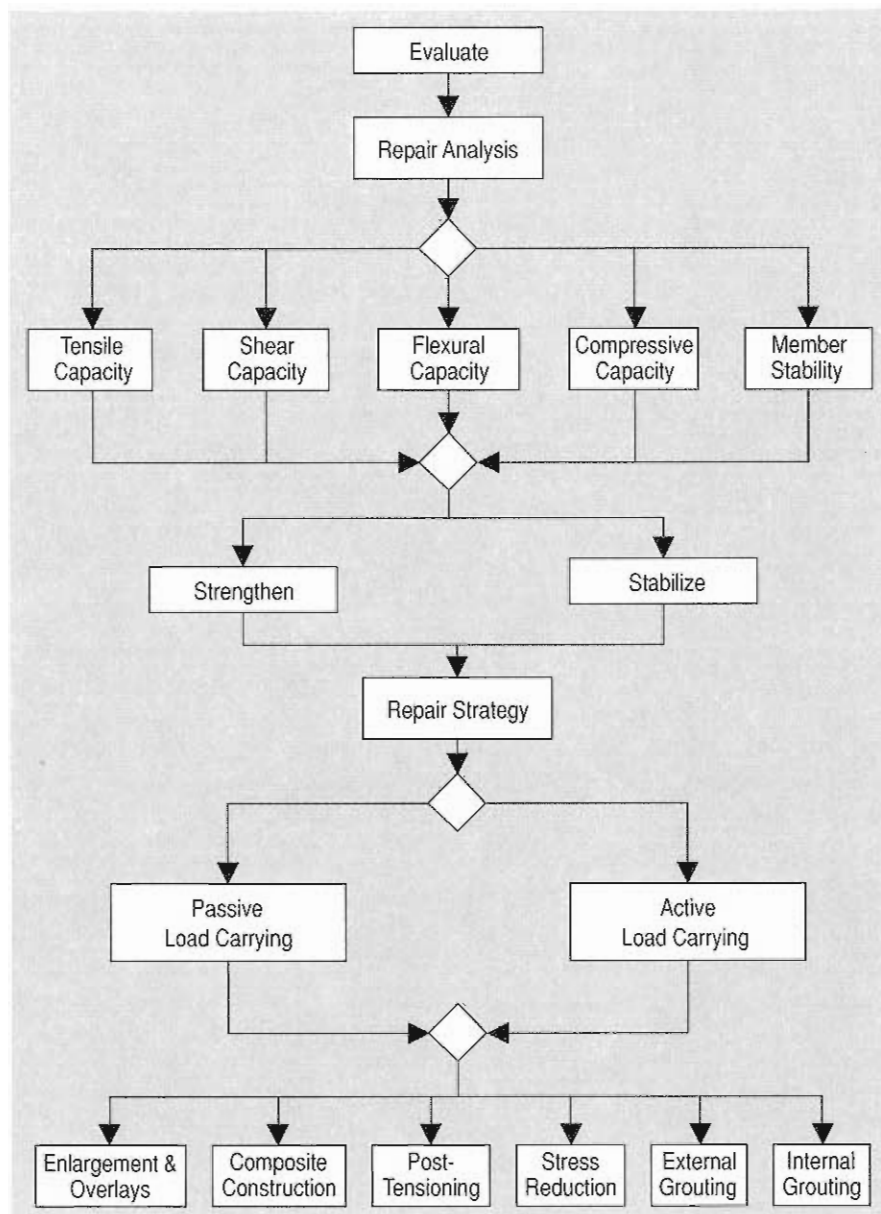
Strengthening and Stabilization

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Introduction to Part Four



When a concrete structure or member exhibits inadequate strength, behavior, or stability, it may be feasible to modify the structure using various stabilization and strengthening techniques. The scope of this book provides conceptual discussion intended to foster the development of ideas for possible solutions. The differences between "stabilization" and "strengthening" are somewhat clouded and, in some cases, are used synonymously.

Stabilization is the process of halting a particular unwanted situation from progressing. Settlement of a structure can be stabilized by grouting to halt further movement.

Strengthening is the process of adding capacity to a member or structure. Concrete jacketing of an existing column will add compressive load-carrying capacity. In some cases, the process involves a combination of halting an unwanted situation and, at the same time, adding capacity. Replacement of a frozen bearing with a new slide bearing assembly will halt the progress of distress and add new freedom of movement.

Section 1: Techniques/Design Considerations

The following topics are covered in this section:

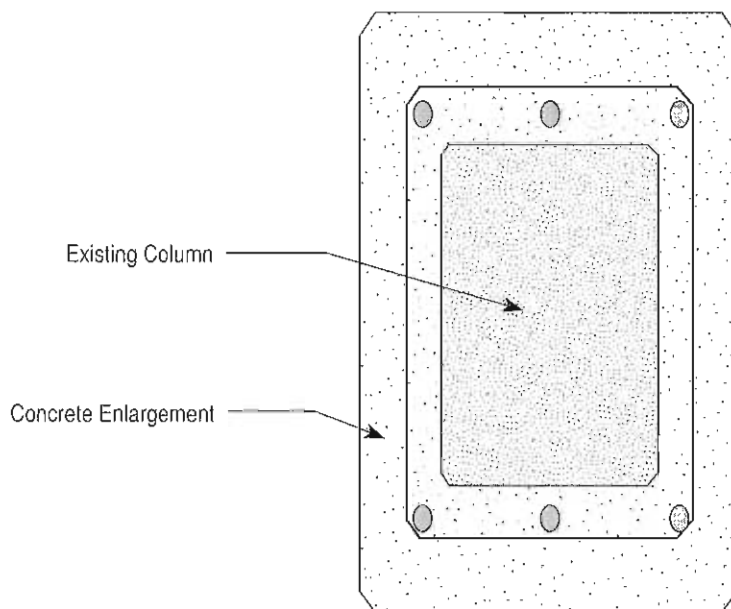
Introduction to Techniques/Design Considerations

Passive and Active Design

Material Behavior

Attachment of Steel to Concrete

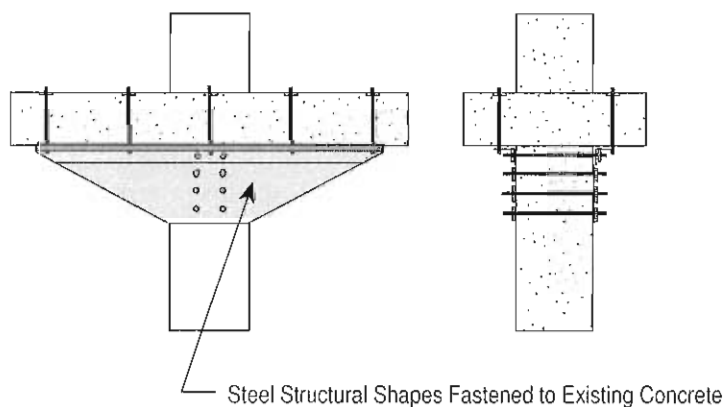
Introduction to Techniques/ Design Considerations



Methods for stabilization and strengthening of concrete structures and members can be categorized by the repair techniques employed.

Enlargement

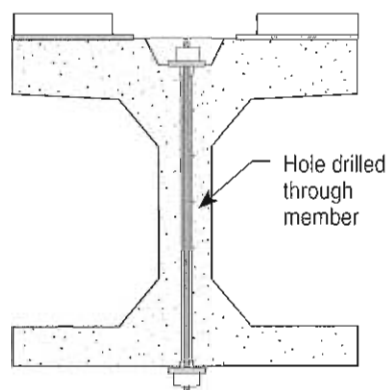
Enlargement is the placement of additional concrete and reinforcing steel on an existing structural member. Beams, slabs, columns, and walls, if necessary, can be enlarged to add stiffness or load-carrying capacity. In most cases, the enlargement is bonded to the existing concrete to create a monolithic member.



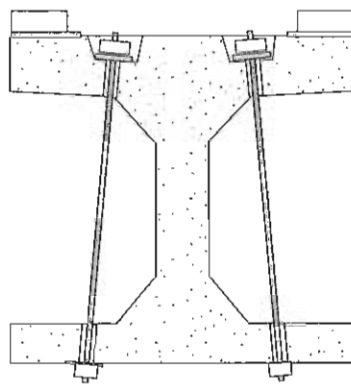
Composite Construction

Composite construction is a method wherein materials other than concrete are placed in concert with an existing concrete member to add stiffness or load carrying capacity. Steel is the most common material used in this technique. Steel plates and structural shapes can be fabricated to meet almost any configuration requirement. Load transfer in the composite member is accomplished by the use of adhesives, grouts, and mechanical anchorage systems.

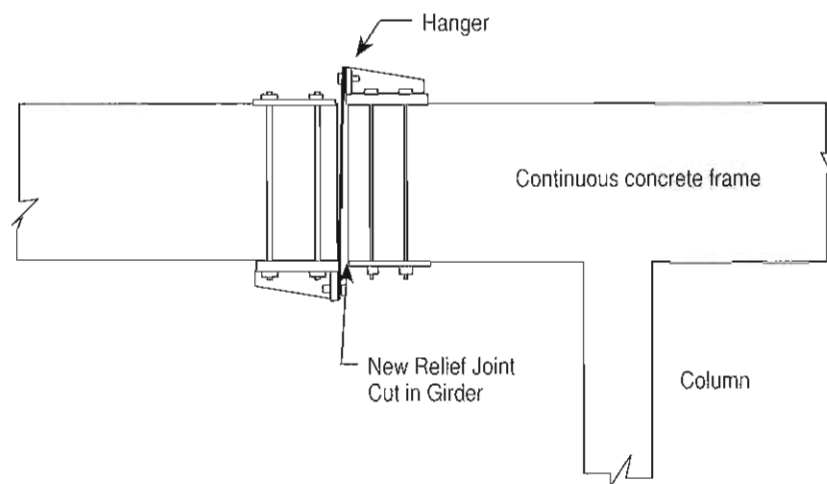
Summary of Techniques



Internally Placed Post Tensioning



Externally Placed Post-tensioning



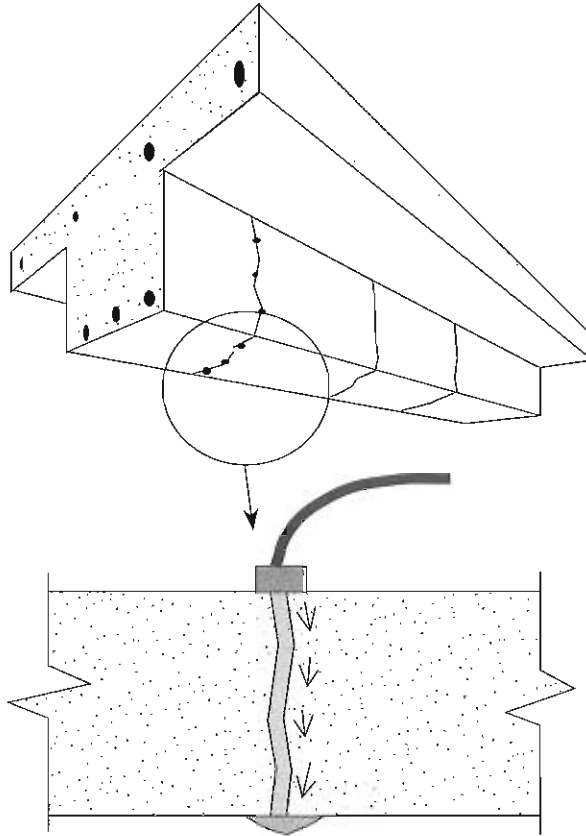
Post-Tensioning

Post-tensioning is a technique used to prestress reinforced concrete. The tensioning provides the member with an immediate and active load-carrying capability.

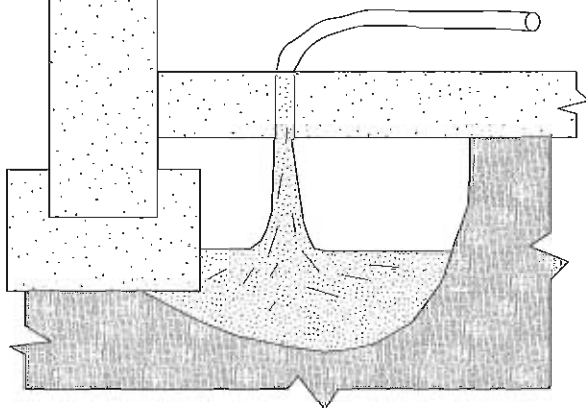
Placement of the tension components can be achieved either internally within the member or externally to the member. Tension components are generally steel plates, rods, tendons or strands. Tension is imparted to the components by jacking or, less commonly, by preheating. Post-tensioning enhances a member's ability to relieve overstressed conditions in tension, shear, bending, and torsion. The post-tensioning technique can also be used to eliminate unwanted displacements in members and to turn discontinuous members into continuous members.

Stress Reduction

Stress reduction is a technique that reduces stress in a member or structure. Some of the more common methods of stress reduction include cutting new expansion joints, jacking displaced structures, and installing isolation bearings. Other more radical techniques involve the removal of portions of structures.



Epoxy Injection Internal Grouting of Crack



External Grouting of Concrete Foundation

Internal Grouting

Internal grouting is the placement of a flowable material into an unwanted discontinuity, such as a crack within the concrete member. The flowable material, upon reaching the discontinuity, will solidify and assume necessary structural properties. Internal grouting is used to repair fractured, honeycombed, or voided concrete placements. The most common materials used for internal grouting are polymers and hydraulic cement-based materials.

External Grouting

External grouting is the placement of a pumpable material outside the structure, generally within the surrounding foundation soils or at the interface between the structure and the soil. The grouting materials can be used either to provide necessary load transfer between the structure and soil, or to displace unwanted settlement. Most materials used for external grouting include cement-based mixtures. Pavement subsealing (slab stabilization) is a specialized external grouting technique used to fill small voids beneath the slab and/or stabilized base that have been caused by pumping action.

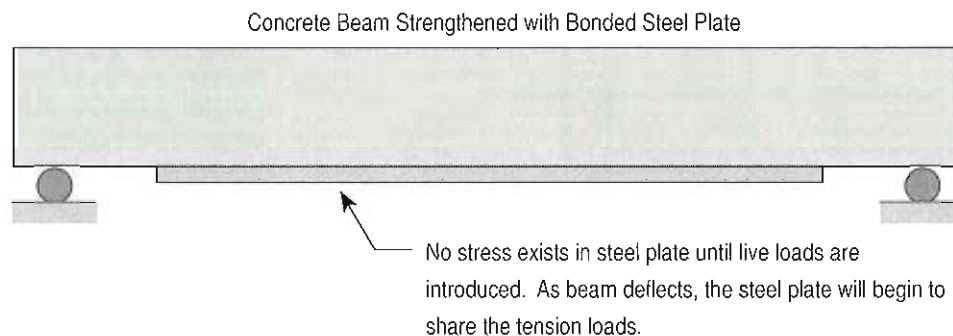
Passive and Active Design

Strengthening and stabilization techniques are generally considered to be either *passive* or *active*, depending on how loads act on the additional components used to strengthen or stabilize the structure. Techniques in which repairs do not participate in stress sharing until additional loads (live or dead) are applied and/or until additional deformation occurs are called *passive*. There are many situations in which additional deformation is not acceptable: the repairs must immediately participate in stress sharing. These repairs are called *active*.

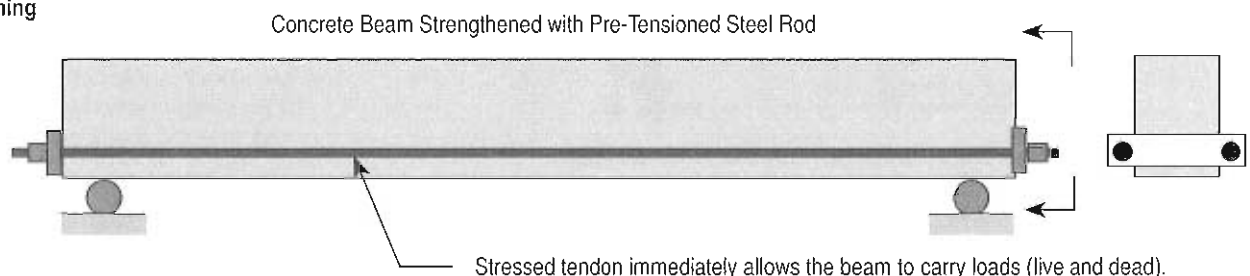
Active systems require either prestressing the repaired elements or temporarily removing the loads (both live and dead) from the existing elements, or a combination of the two. Active systems can be compared to elastic suspenders used to hold up pants. If the suspenders are placed in tension immediately (active), the pants will stay in their vertical position. On the other hand (passive), if the suspenders are placed loose or without tension, the pants will fall vertically until sufficient tension occurs in the suspenders to resist the weight of the pants.

Passive systems work well when live load changes are anticipated. For example, upgrading a bridge to sustain heavier loads may require only a passive system. However, if a member is overstressed, the only choice may be to use an active repair technique that will immediately reduce the stress by sharing the loads, thus, eliminating the overstressed condition.

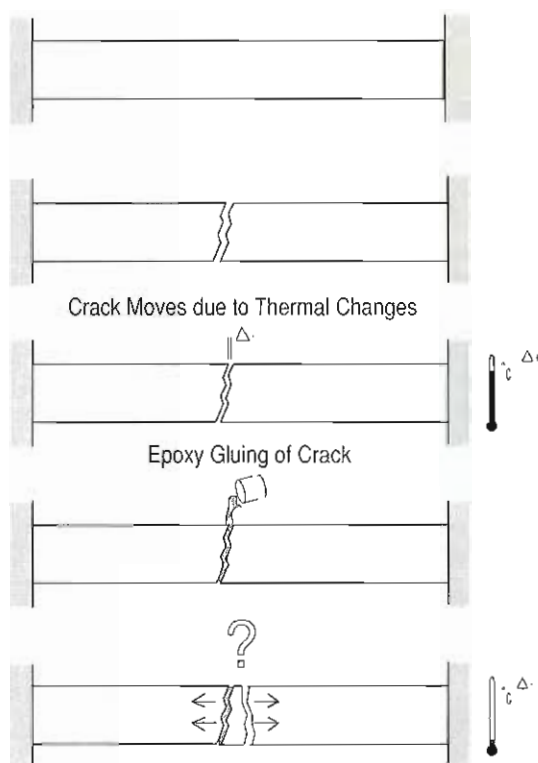
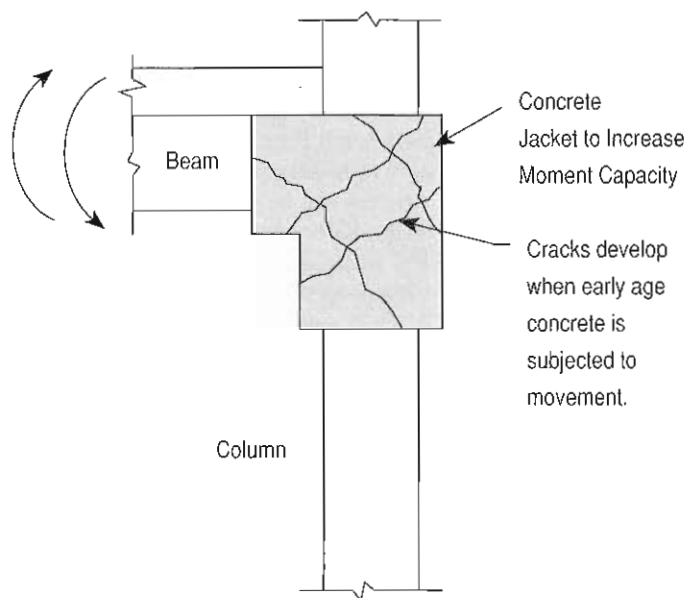
Passive Strengthening



Active Strengthening



Material Behavior



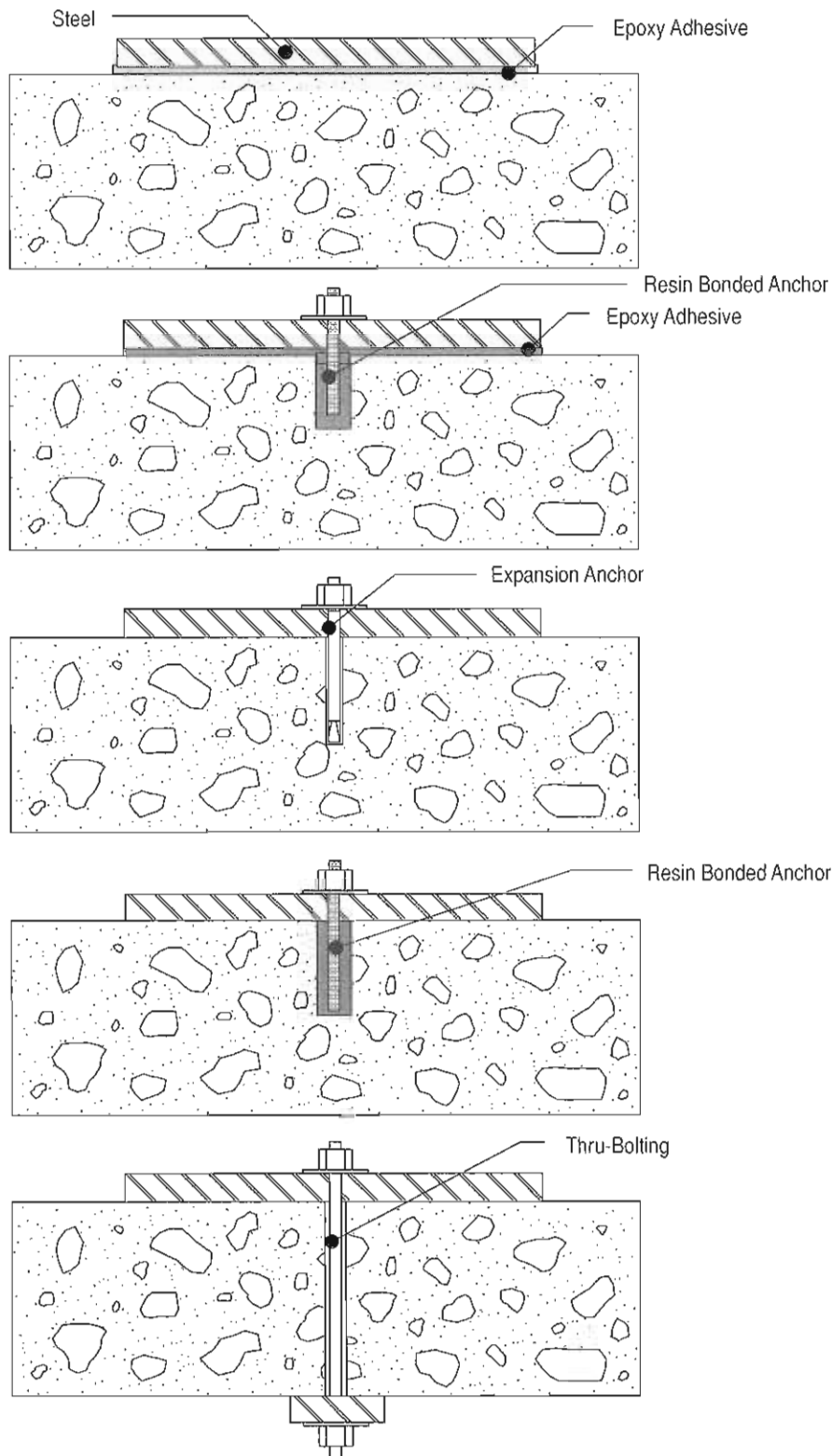
Epoxy injection may not be successful if excessive movement occurs.

It is important to understand material behavior when considering repairs involving stabilization and strengthening. One must consider material behavior, not only in its cured state, but also during the placement and curing processes.

Many stabilization and strengthening techniques involve the use of polymers, cement-based mortars, and concretes. These materials are weak during the curing process. If they are interfered with during this period, the result may be a less-than-anticipated performance. For example, when strengthening beam-column connections to increase moment capacity, some of the connections may be subject to continuous movement (rotation) from diurnal solar heating (Part One—Section Four, "Uneven Thermal Loads"). If the repair includes the construction of a concrete collar, fracturing of the concrete will occur in the first 24 hours, rendering the repair questionable. A better solution, in this situation, would be to use steel plates in combination with embedded anchors and rapid-setting bonding adhesives.

When considering strengthening and stabilization techniques, it is also important to consider both the static and the dynamic behavior of the structure or members involved. A cracked beam may seem static, but in many cases, the crack moves slightly due to changing live loads or thermally-induced strain. These movements may not be noticeable to the naked eye, but when the crack movement is measured with instruments, the crack may exhibit regular and significant movement. Many repairs fail when epoxy is injected into moving cracks. Once epoxy is placed and cured, and the crack moves, tensile stress develops. If the tensile stress exceeds the tensile capacity of the member, a new crack will often develop adjacent to the existing repaired crack.

Attachment of Steel to Concrete



Repair techniques often require an attachment of steel to concrete. Many strengthening and stabilization techniques utilize steel to strengthen connections or provide additional tensile capacity. Attachment methods utilize mechanical connections and/or adhesives, permitting load transfer (shear, tension, or compression) between the steel and concrete. Use of adhesives as a connecting mechanism provides for uniform load transfer and corrosion protection at the concrete-steel interface. For maximum bond, the steel requires a high level of abrasive cleaning (white metal, near white, commercial). The concrete surface requires roughening by mechanical or abrasive/liquid blast methods and removal of surface laitance. Mechanical anchorage methods utilize different types of anchor devices. Where vibration exists in the connection, resin anchors or through-bolting should be utilized. In critical applications, a combination of adhesives and mechanical systems should be considered.

Section 2: Beam Shear Strengthening

The following topics are covered in this section:

Introduction to Beam Shear Strengthening

Internally Placed Passive Shear Strengthening

Beam Shear Capacity Strengthening at Moving Hinge

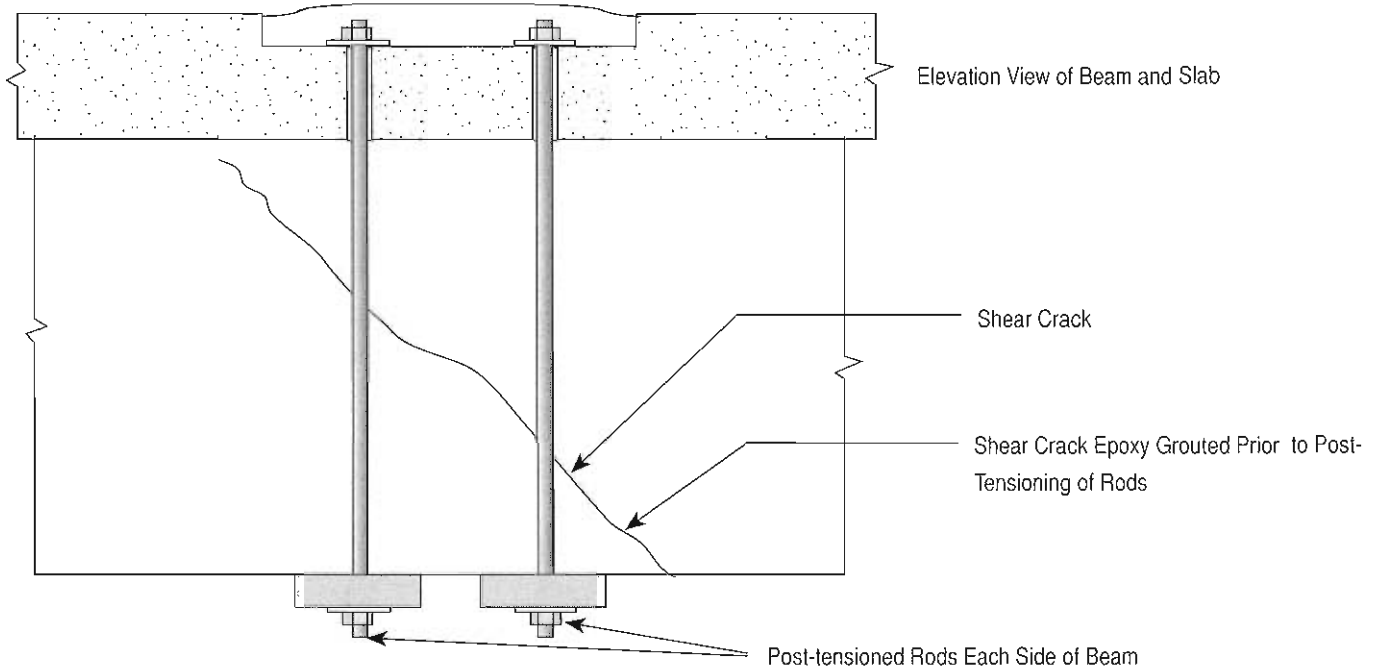
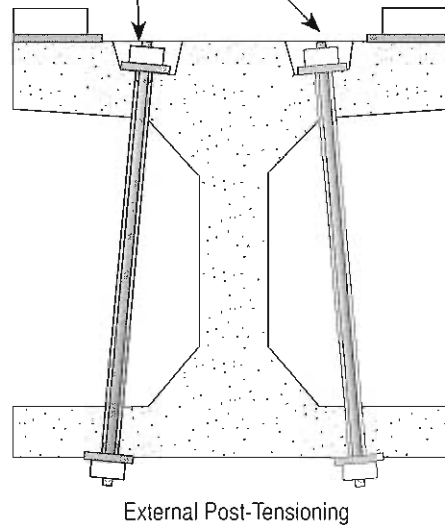
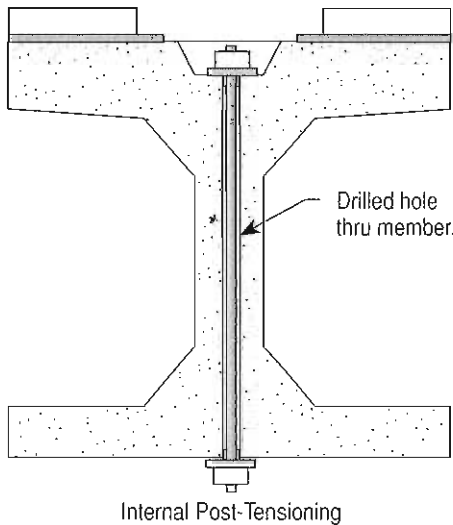
External Post-Tensioned Straps

Introduction to Beam Shear Strengthening

Externally placed requires load balancing on each side of member.

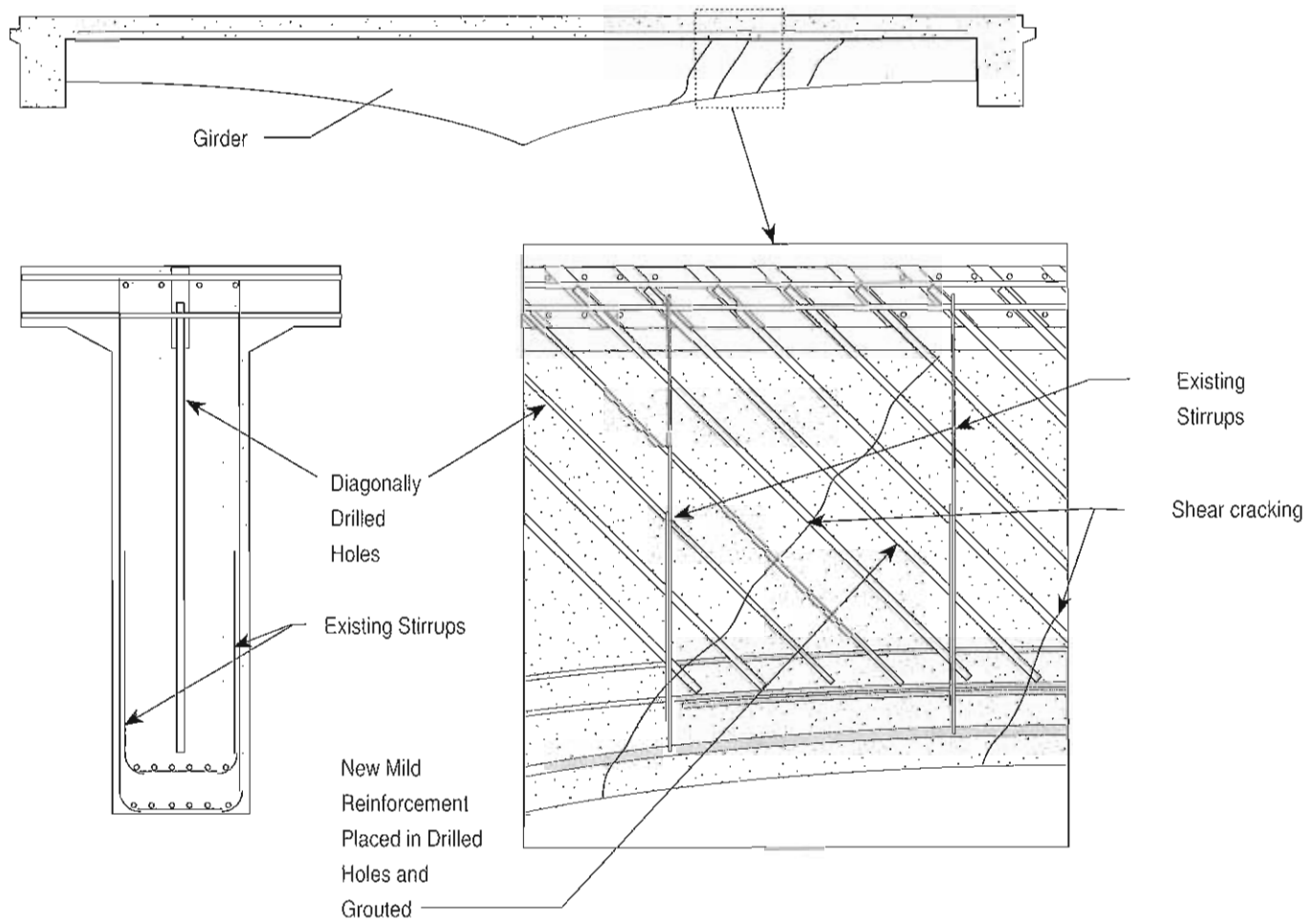
Beam shear capacity can be increased by using various strengthening techniques, including:

- external post-tensioning
- internal post-tensioning
- internal mild steel reinforcement
- bonded steel members
- enlarging member's cross-section



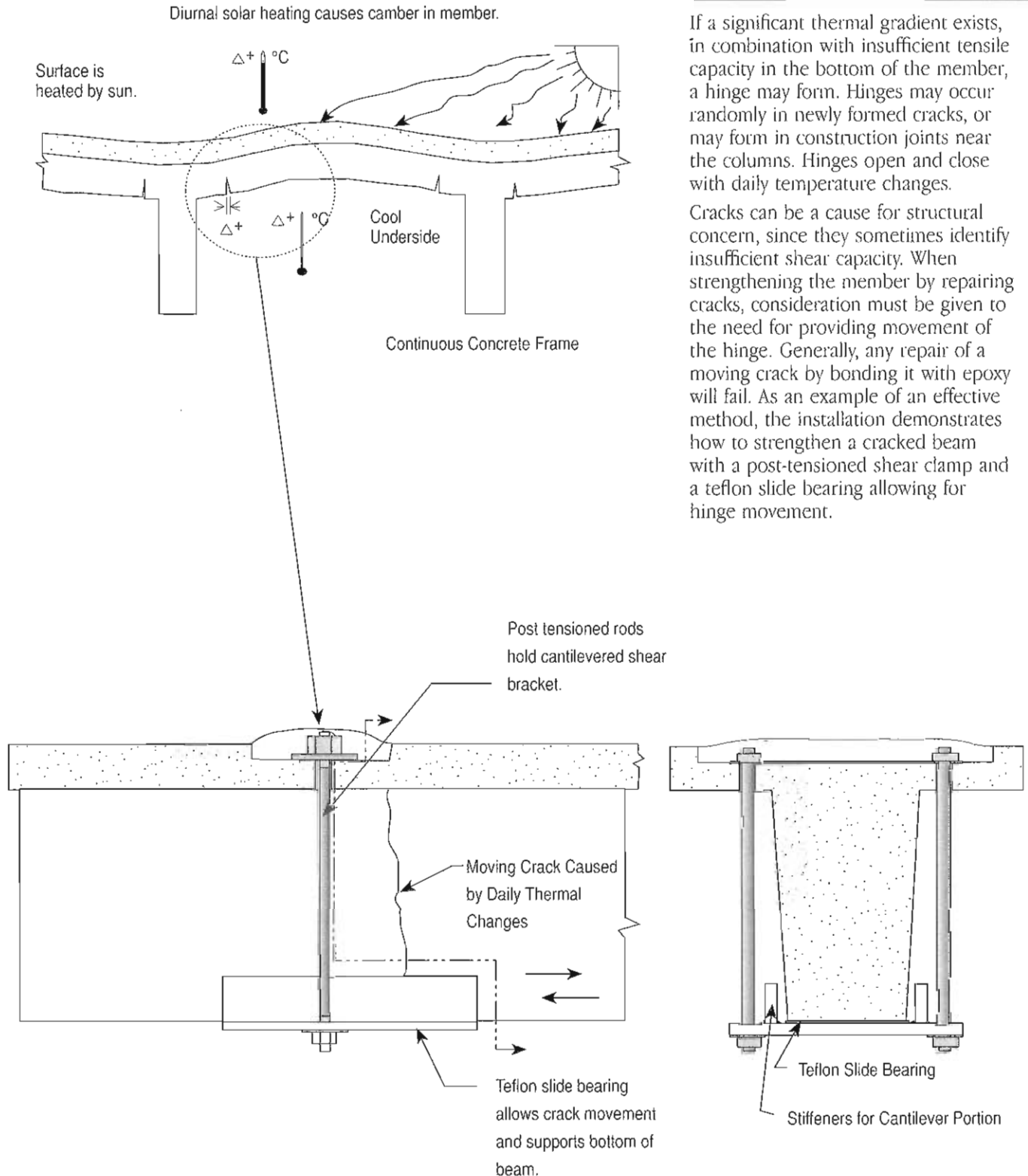
Internally Placed Passive Shear Strengthening

Strengthening of existing members to increase their shear capacity can be performed by adding shear reinforcement. For example, the Kansas Department of Transportation has used mild reinforcement dowels inserted perpendicular to the direction of shear cracking, into drilled holes. The dowels are then grouted into place with epoxy.¹



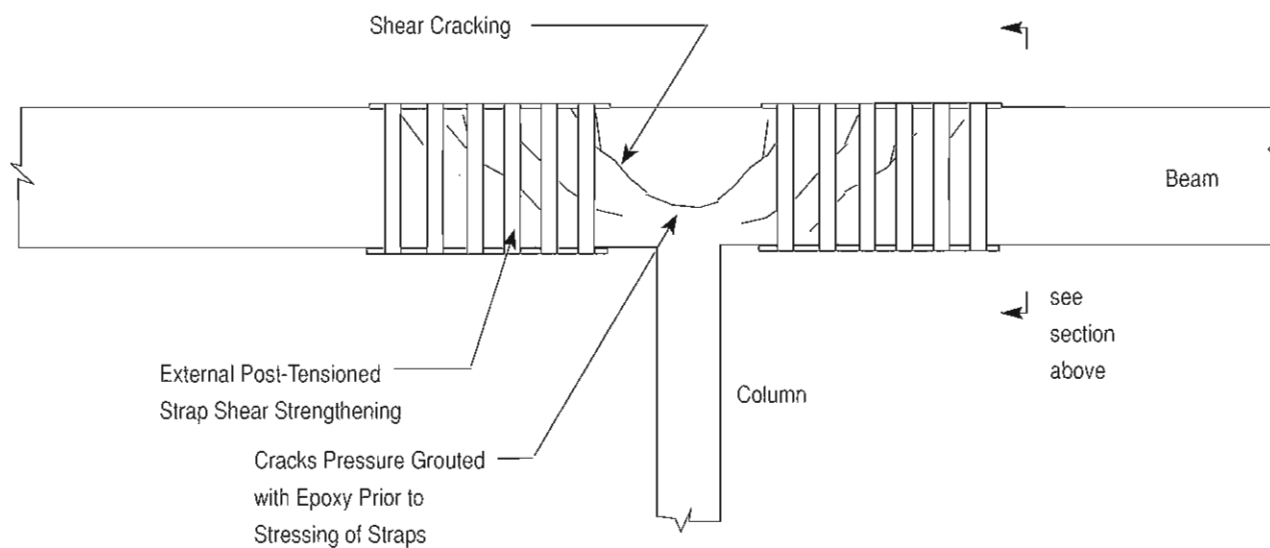
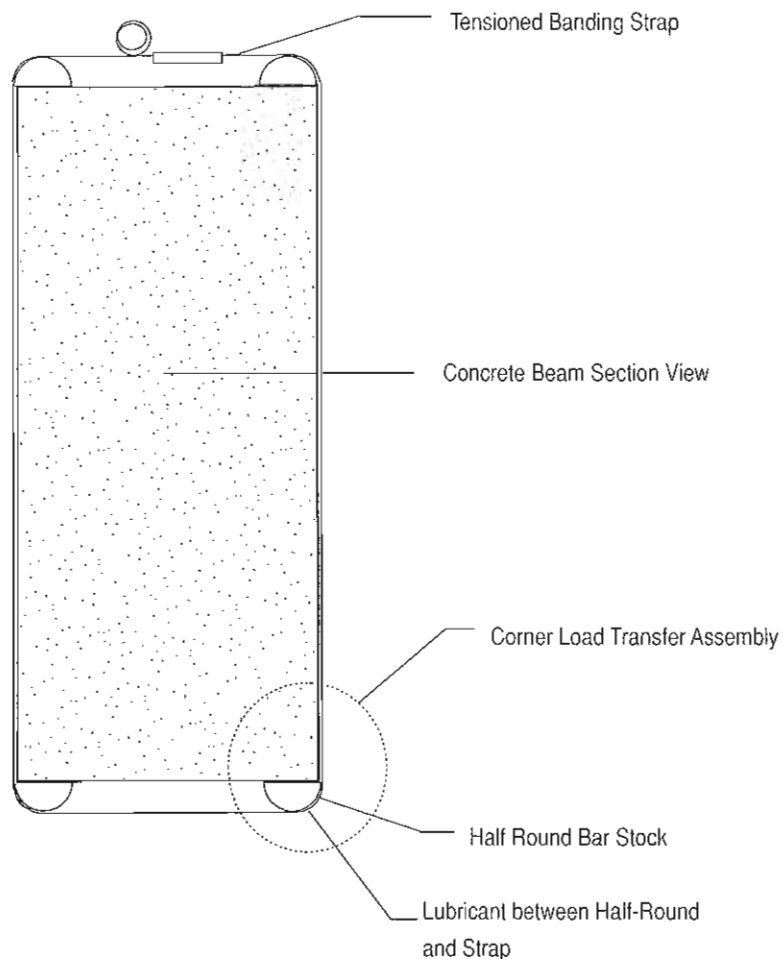
¹Stratton, F.W., Alexander, R.B. and Nolting, W.R., Development and Implementation of Concrete Girder Repair by Post-Reinforcement, Kansas Department of Transportation, 1982, 31pp.

Beam Shear Capacity Strengthening at Moving Hinge



External Post-Tensioned Straps

2" wide strap can carry approximately
10,000 pound force (44,480 N).



Section 3:

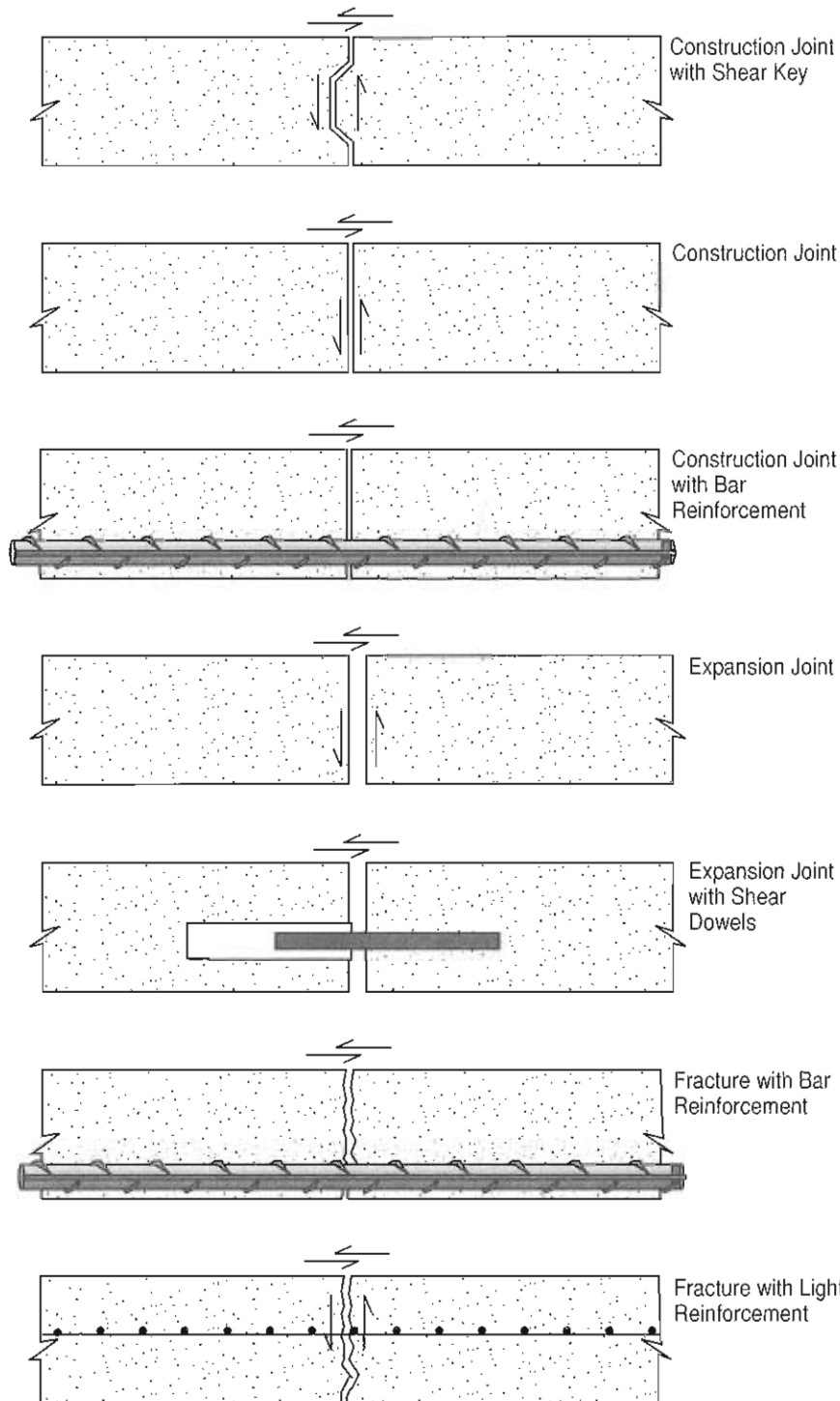
Shear Transfer Strengthening Between Members

The following topics are covered in this section:

Introduction to Shear Transfer
Strengthening Between Members
Dowel Shear Device
Drilled Hole Shear Transfer Device
Grouted Subgrade
Cantilevered Shear Arm

Introduction to Shear Transfer Strengthening Between Members

Types of junctions between members



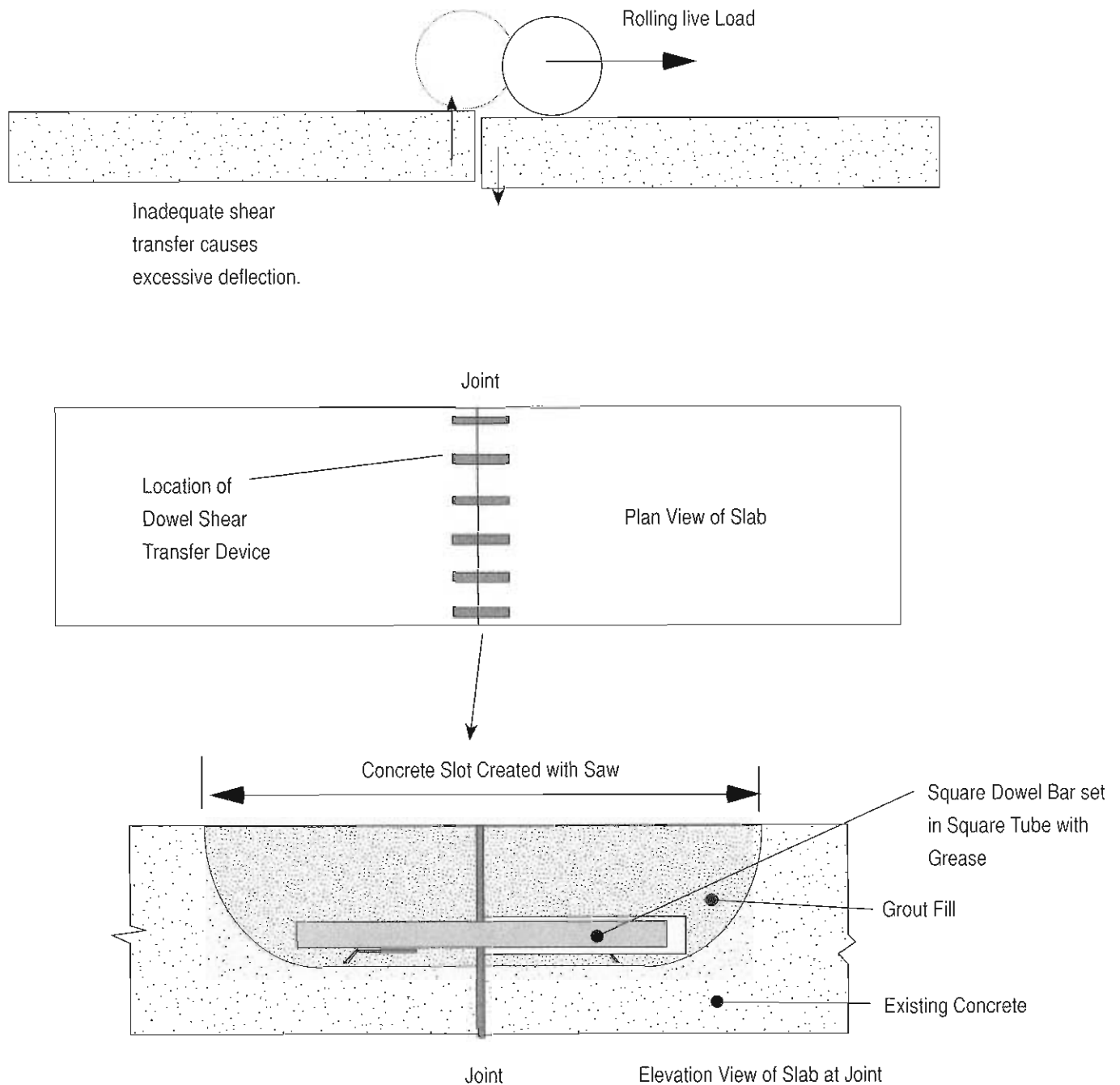
Proper shear transfer between slabs and between other structural members is important when wheel loads cross the joint. The ability of a joint to transfer load (shear) from one side to another is very important to slab performance. Poor load transfer results in the following:

- High deflections causing increased pumping and subsequently faulting.
- Loss of support beneath the slab resulting in slab breakup.

Such problems most commonly occur in slab-on-grade and precast elevated floor systems. Techniques available for strengthening and stabilizing to achieve proper shear transfer include:

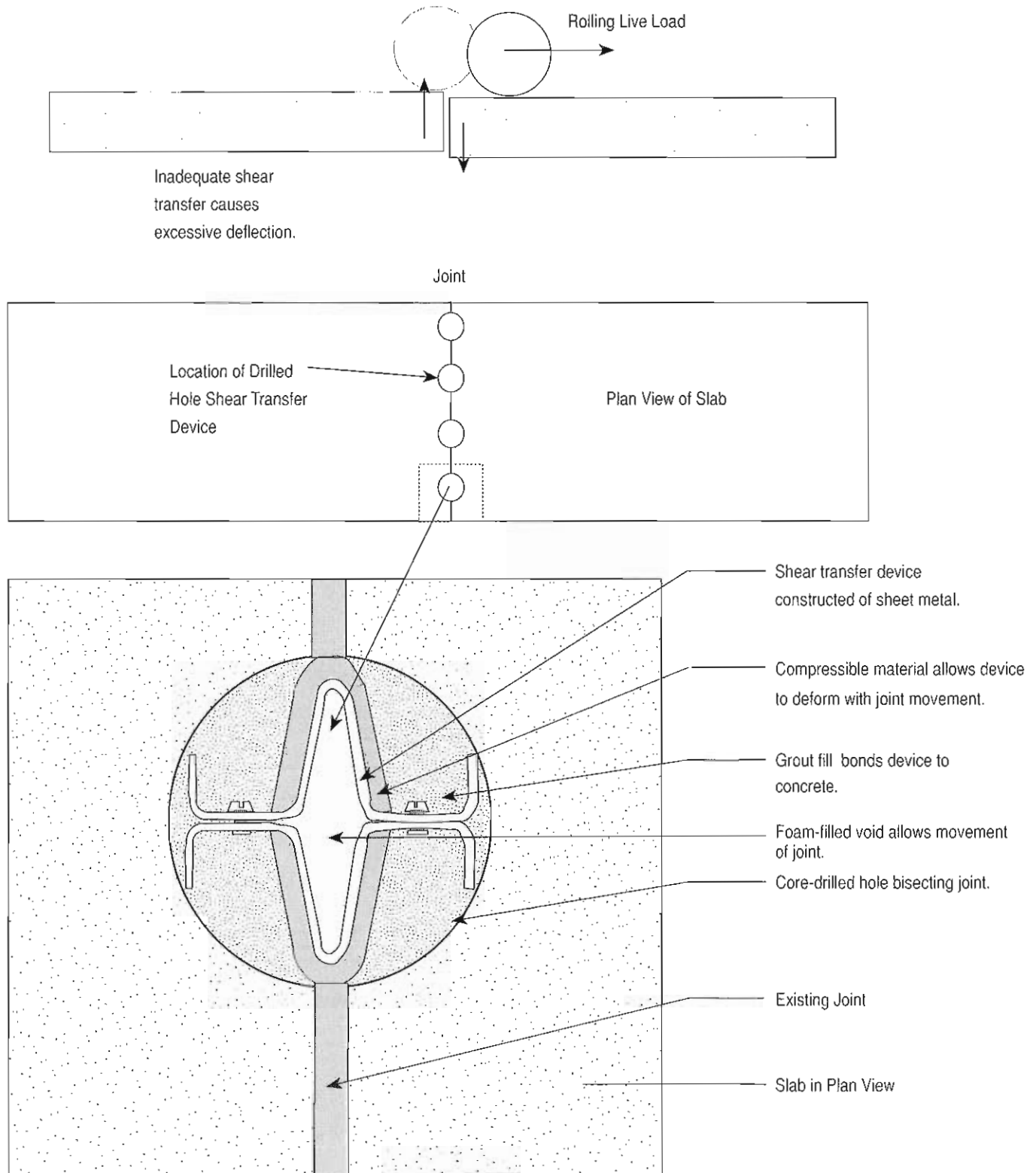
- dowel shear device
- drilled hole shear transfer device
- sawed slot dowel transfer device
- alternating cantilever
- hinge plate
- slab subsealing/slab jacking

Dowel Shear Device

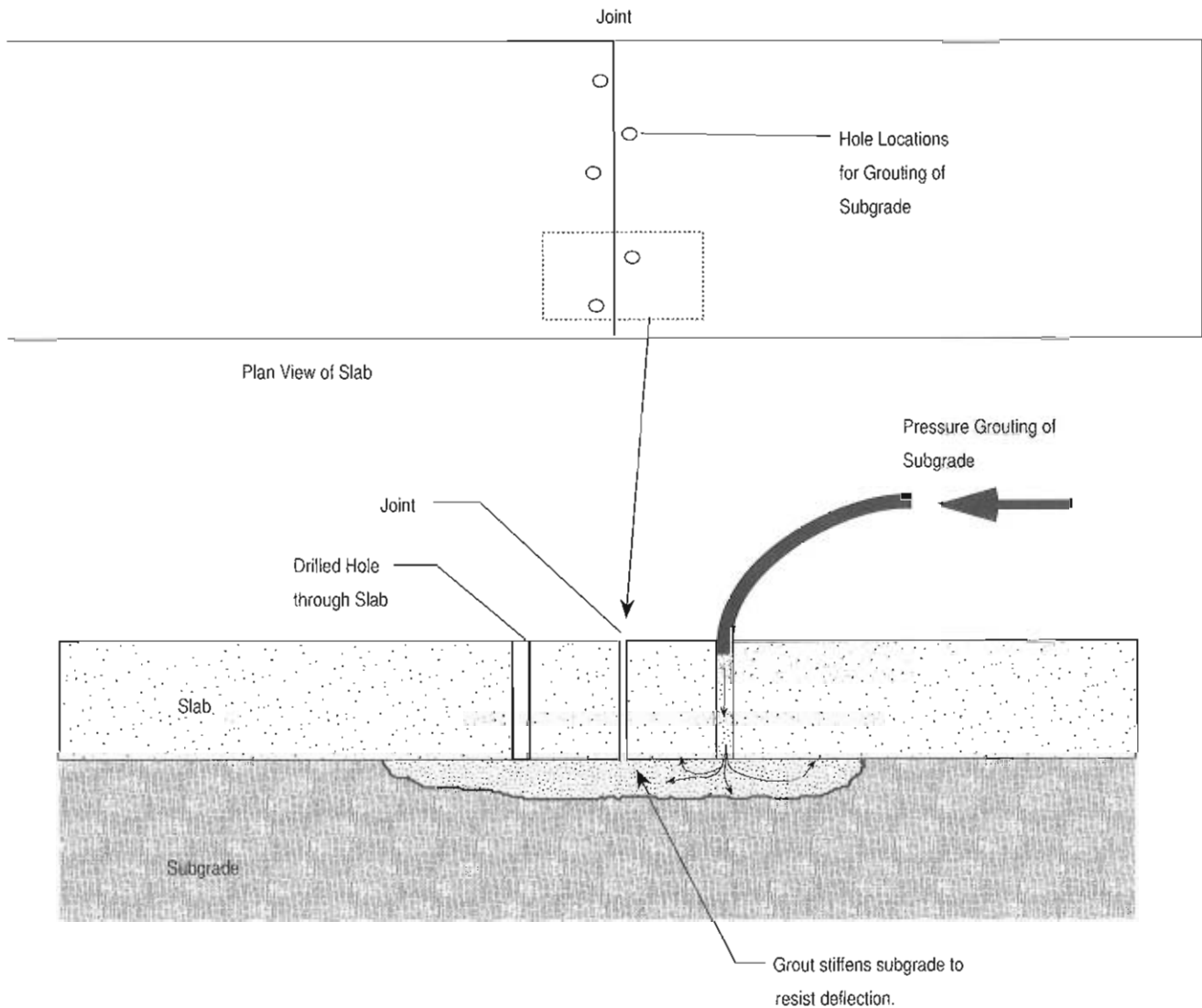
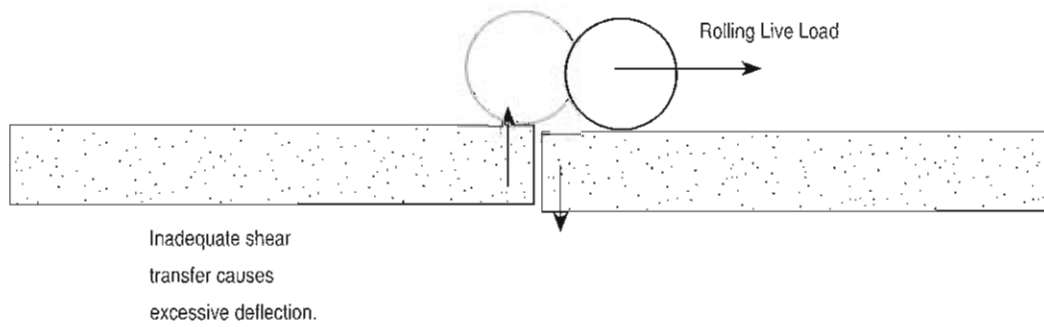


Caution: Misaligned dowels may cause stress buildup and cracking.

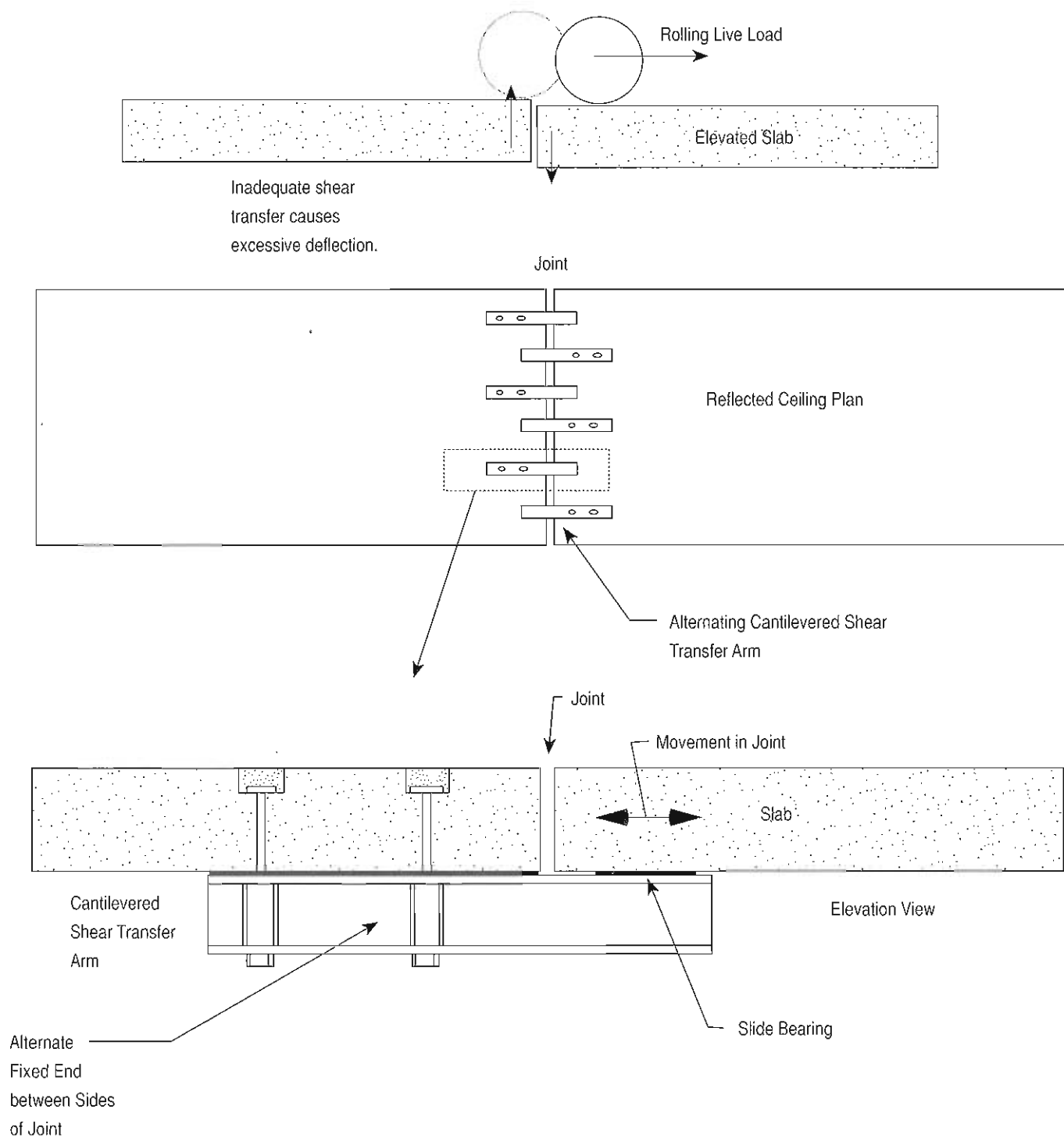
Drilled Hole Shear Transfer Device



Grouted Subgrade



Cantilevered Shear Arm



Section 4:

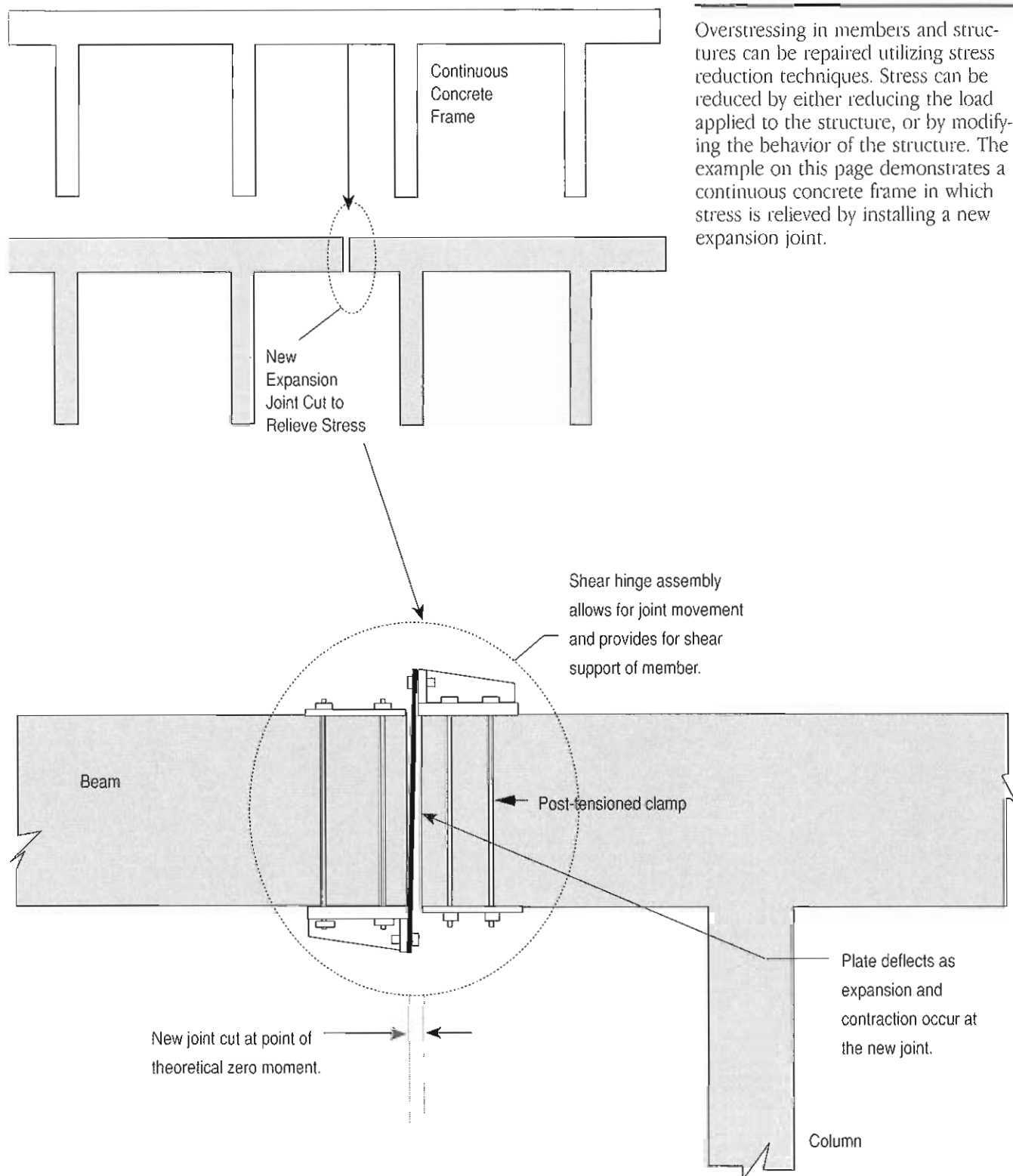
Stress Reduction Techniques

The following topics are covered in this section:

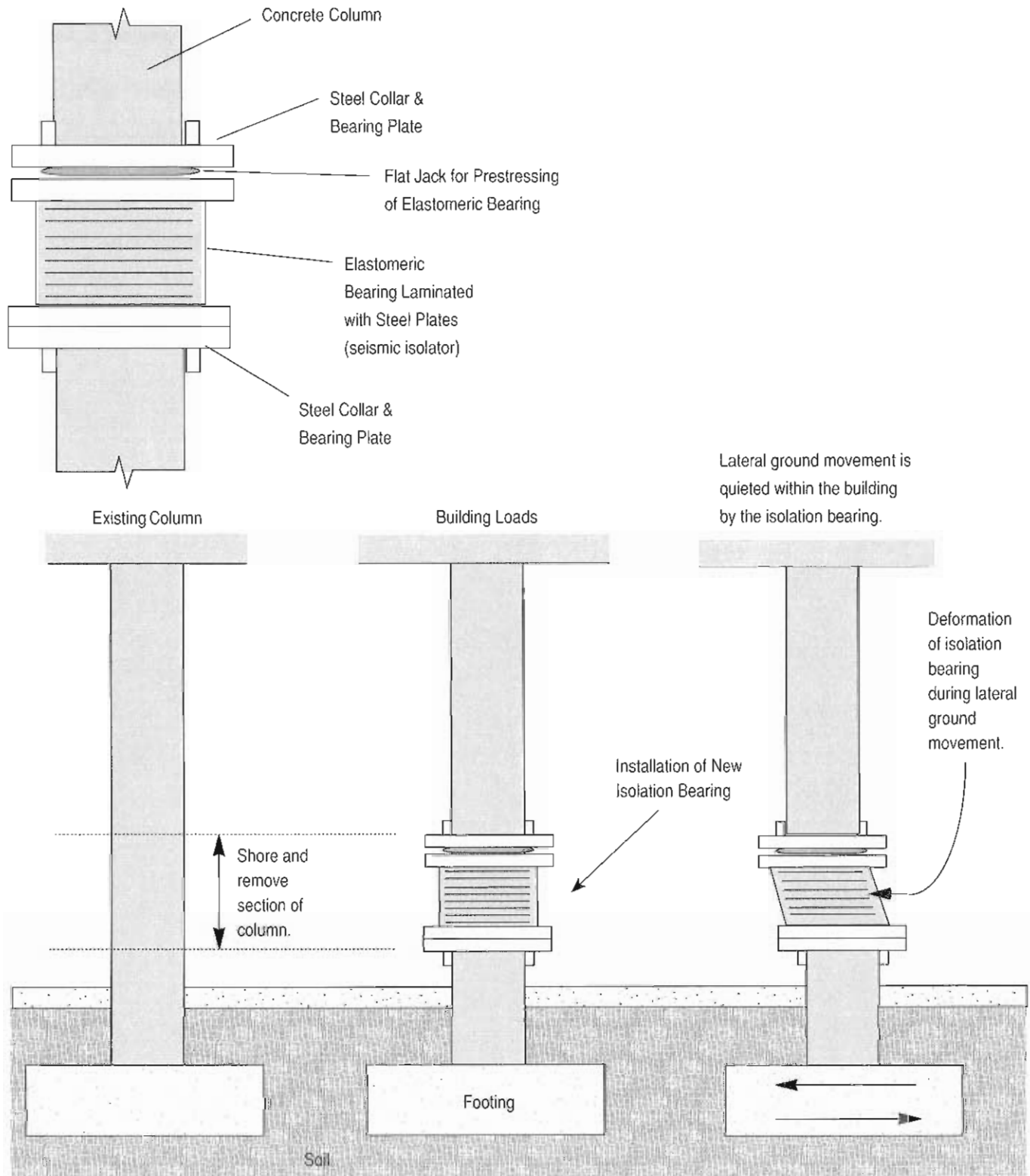
Installing New Expansion Joint in
Continuous Concrete Frame

Lateral Ground Movement Isolation

Installing New Expansion Joint in Continuous Concrete Frame



Lateral Ground Movement Isolation (Seismic Isolation)



Section 5: Column Strengthening

The following topics are covered in this section:

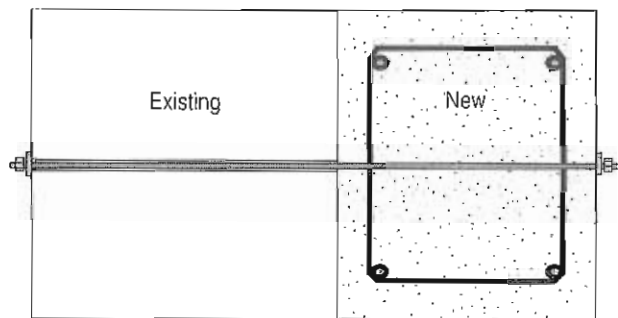
Compressive Strengthening by
Enlargement

Shear Capacity Strengthening Using
Shear Collars

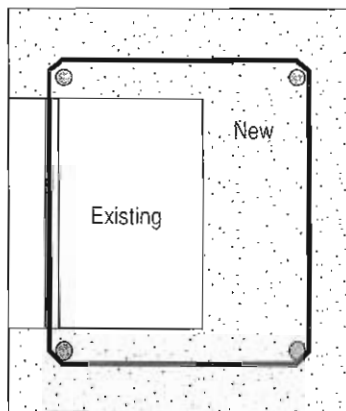
Beam-column Moment Capacity
Strengthening

Confinement strengthening

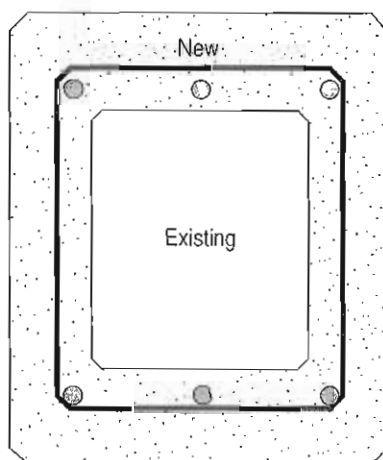
Column Compressive Strengthening by Section Enlargement



Method A



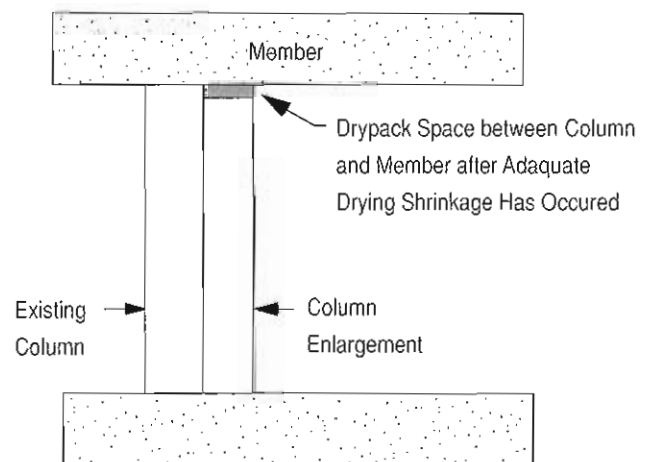
Method B



Method C

Enlarging the cross section of an existing column will strengthen the column by increasing its load carrying capacity. A column can be enlarged in various configurations. However, the drying shrinkage effects in the concrete used to enlarge the column must be considered. Drying shrinkage, if restrained, will induce tensile stresses in the new portion of the column.

In the illustration, Method A will accomplish efficient load transfer if the new portion is cast with a bond breaker between the new and old concrete. After most of the drying shrinkage has occurred, the ties that link the old and new concrete can be installed. The gap between the new portion of the column and the existing member (to be partially supported by this column) can be filled with dry-packing material. This will allow the new material to share its portion of the load. When Methods B and C are used, extreme care should be exercised to select concrete mix designs with very low shrinkage rates. Pre-placed aggregate concrete generally offers the lowest drying shrinkage; it is, therefore, an excellent material for column enlargements.



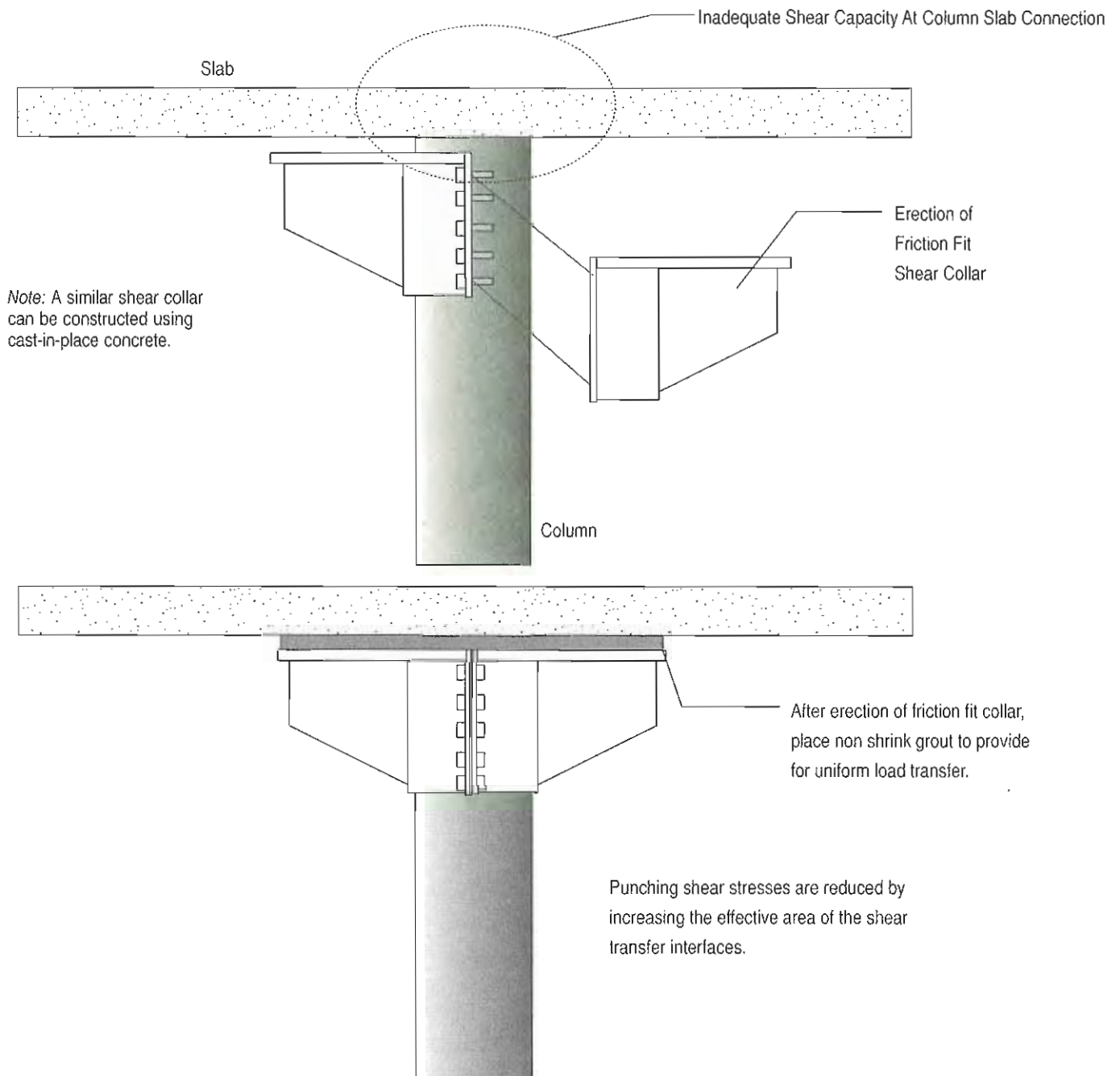
Elevation view of Method A

Shear Capacity Strengthening Using Shear Collars

Shear stress occurs at the connection of floor systems and columns. When additional shear capacity is required to

resist punching shear, the following techniques are often used:

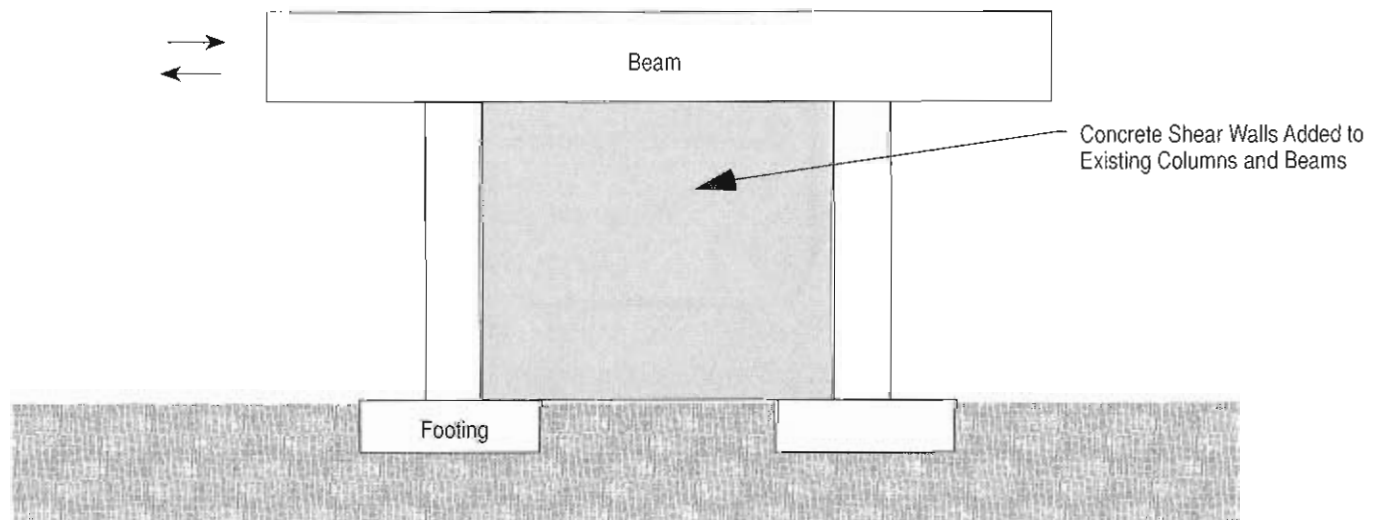
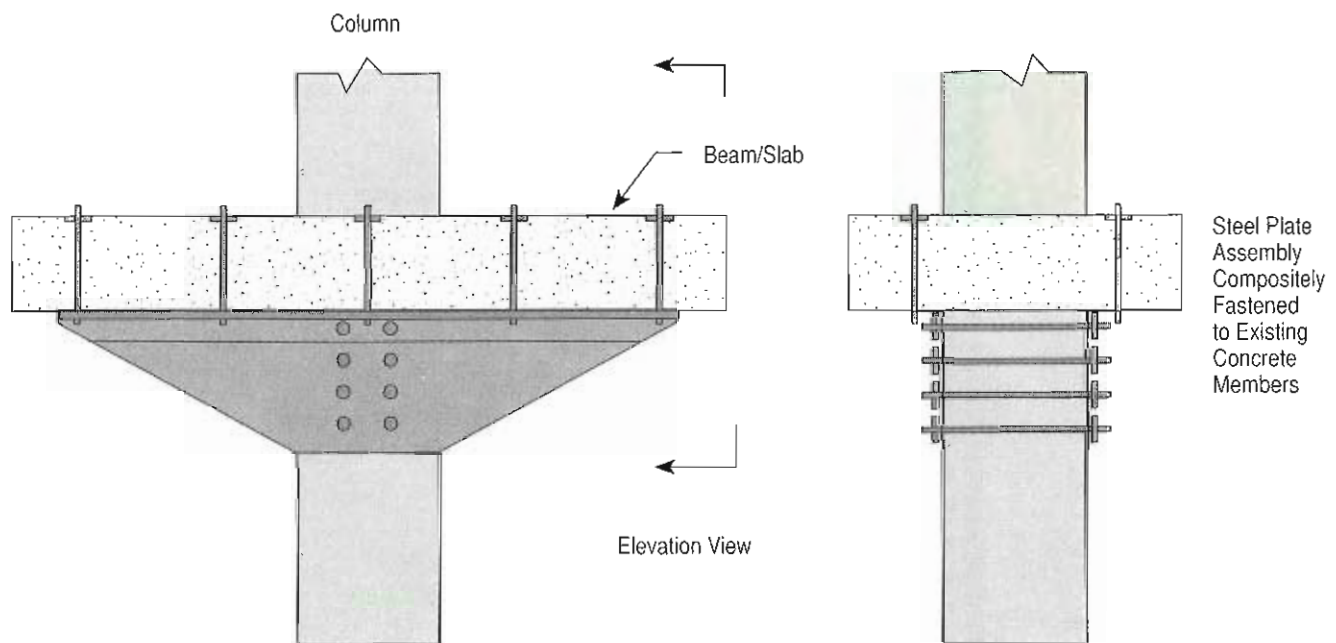
- column section enlargement
- composite bonded steel shear collars



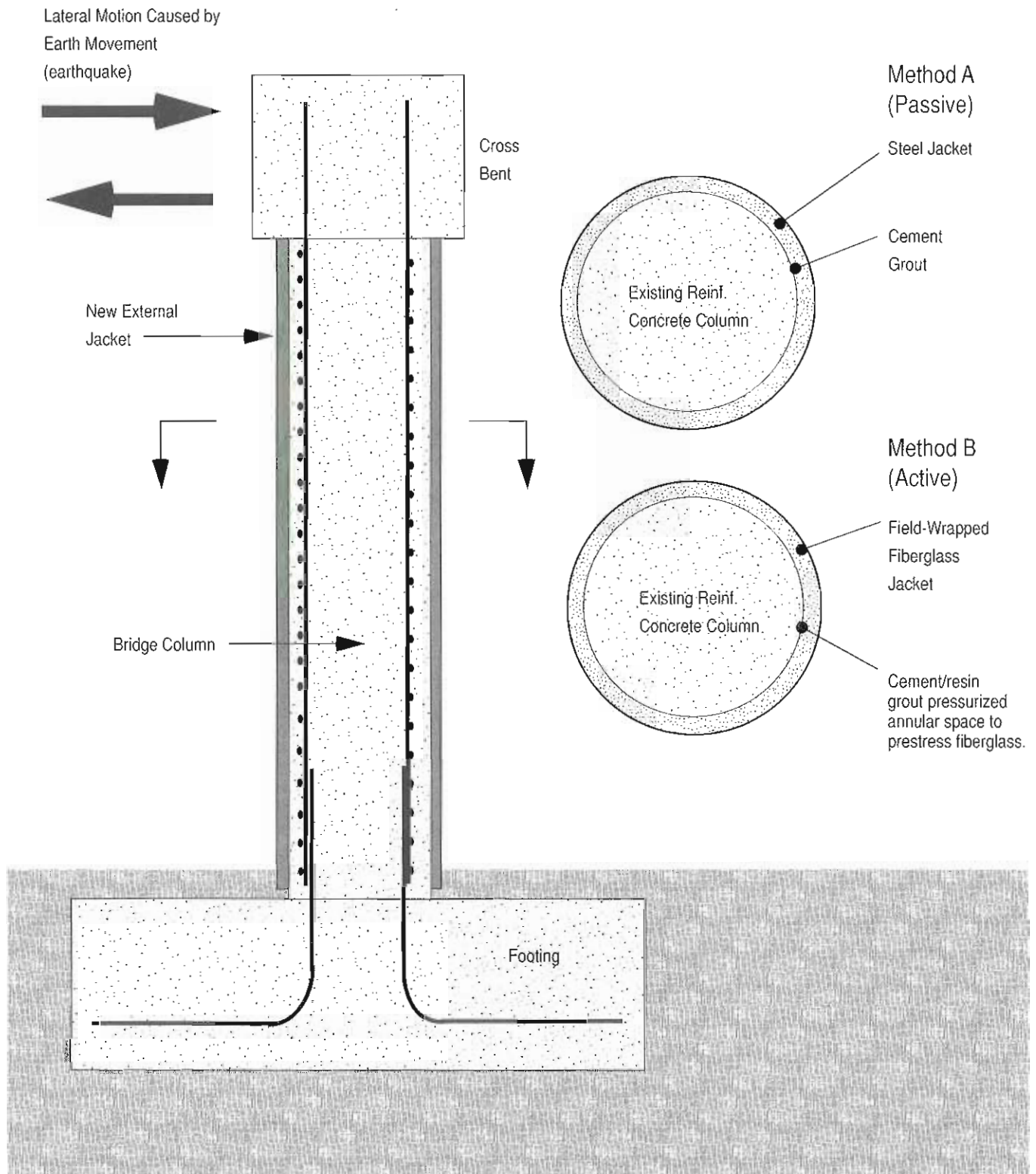
Beam-Column Moment Capacity Strengthening

Beam-column connections can be strengthened using various techniques including:

- bonded steel members
- concrete overlay
- continuous external column confinement
- shear wall construction



Confinement Strengthening



Section 6:

Flexural Strengthening

The following topics are covered in this section:

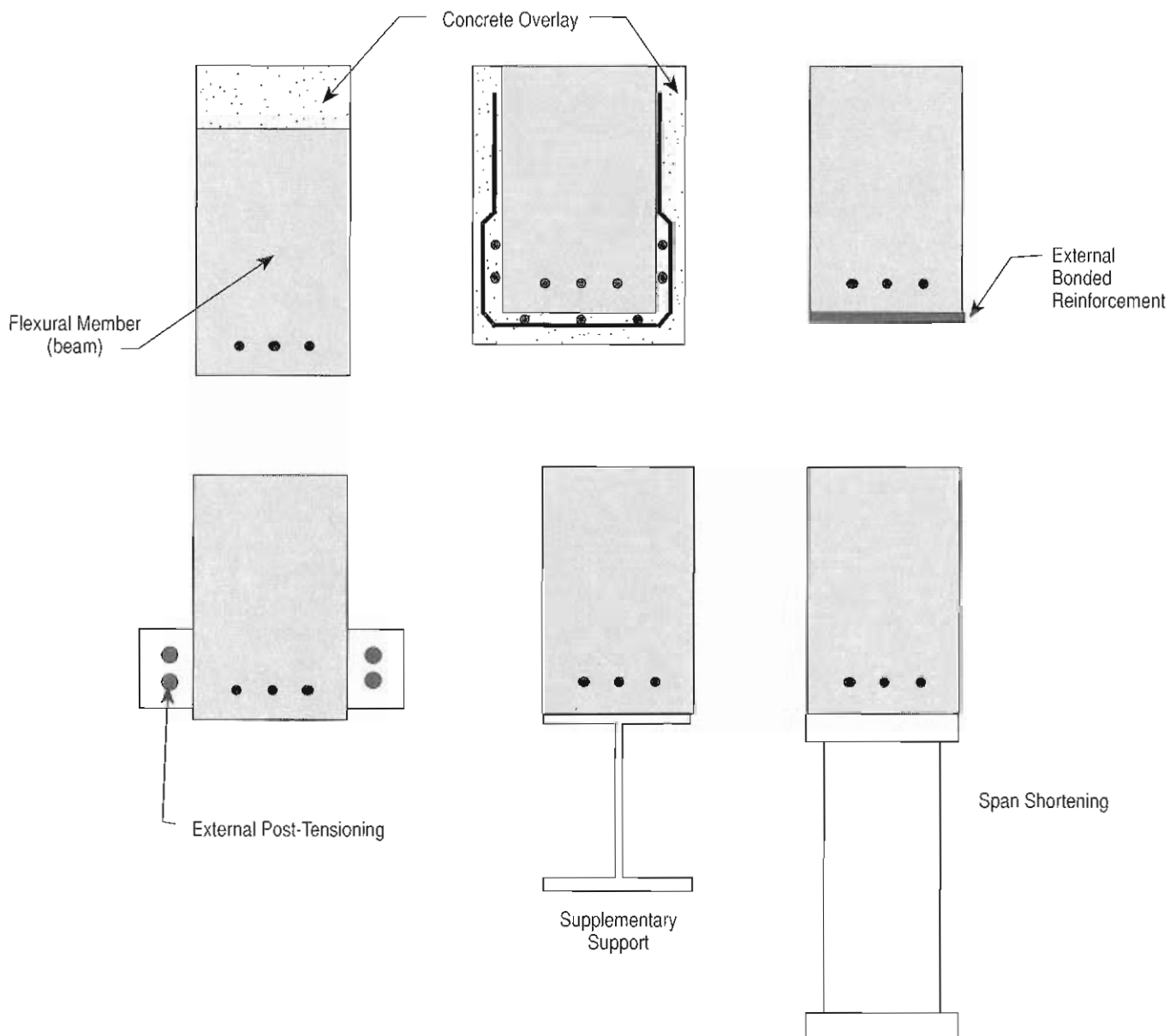
Summary of Methods
External Post-Tensioned Reinforcement
Span Shortening Techniques
Bonded Steel Plate Reinforcement
Correction of Deflected Member with Bonded Steel Plate
Concrete Overlay and Section Enlargement
Wall Strengthening

Summary of Methods

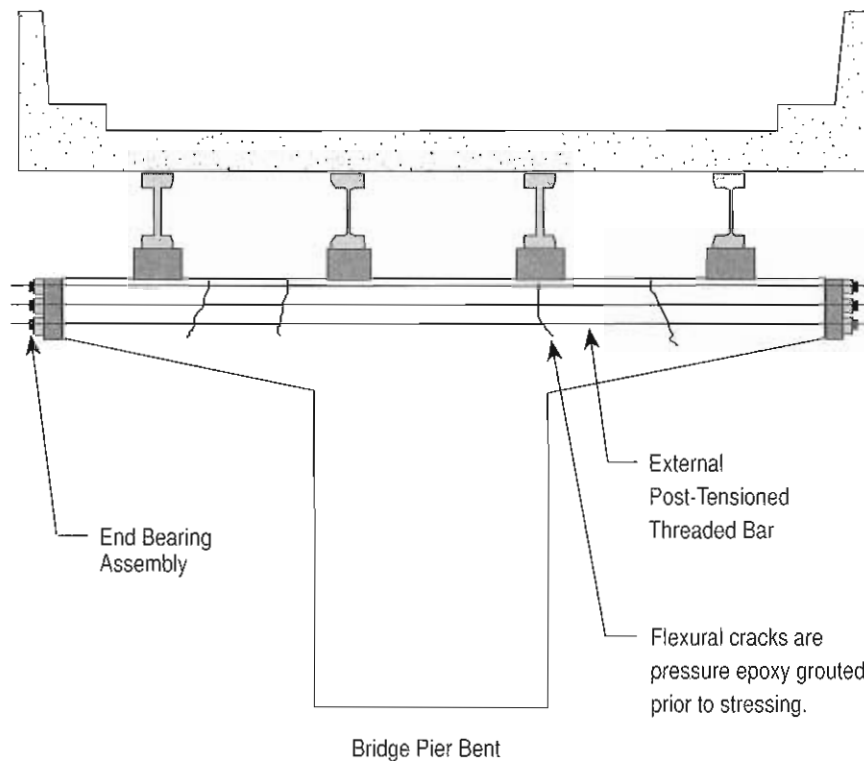
Beam and Slab Flexural Strengthening

The flexural capacity of concrete members requires an increase when either a design deficiency is uncovered, excessive deflection occurs, or additional loads are anticipated. Various techniques used to increase flexural capacity include:

- concrete encasement
- external post-tensioning
- externally bonded reinforcement
- concrete overlays
- span length shortening
- supplemental support



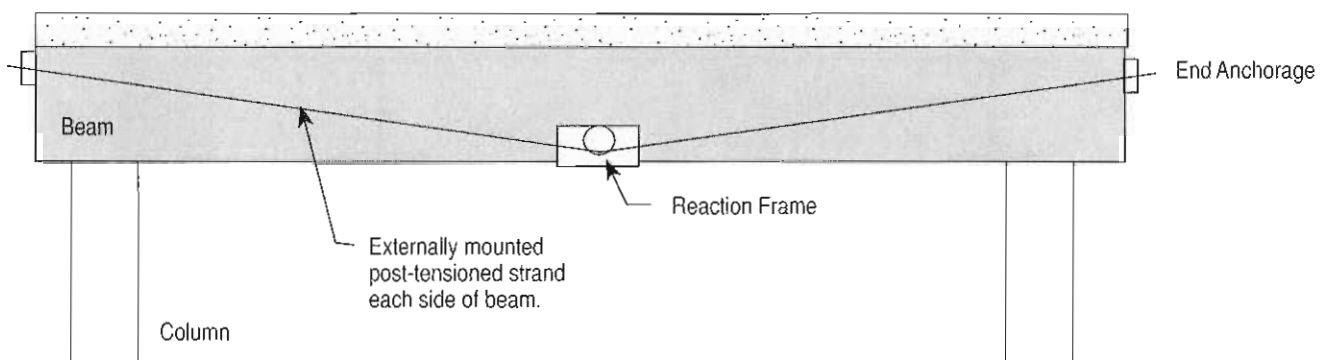
External Post-Tensioned Reinforcement



The use of external post-tensioned reinforcement is an excellent method of increasing flexural capacity or replacing damaged prestressed strands. Different types of hardware are available, providing various load configurations and corrosion protection. High-strength thread bar is commonly used for straight lengths, and strand is generally used where drape is required. External post-tensioning provides for immediate and active participation in both dead and live load distribution. Prior to the prestressing, any flexural cracks should be pressure-grouted with epoxy for uniform compression distribution.

Attachment of external post-tensioning hardware to the existing structure requires either a shear transfer mechanism or an end bearing assembly. The shear transfer mechanism is usually side-mounted or soffit-mounted to the flexural member, and bolted through to provide sufficient shear transfer. In some applications, the strand or bar is deflected at midspan using a saddle clamp.

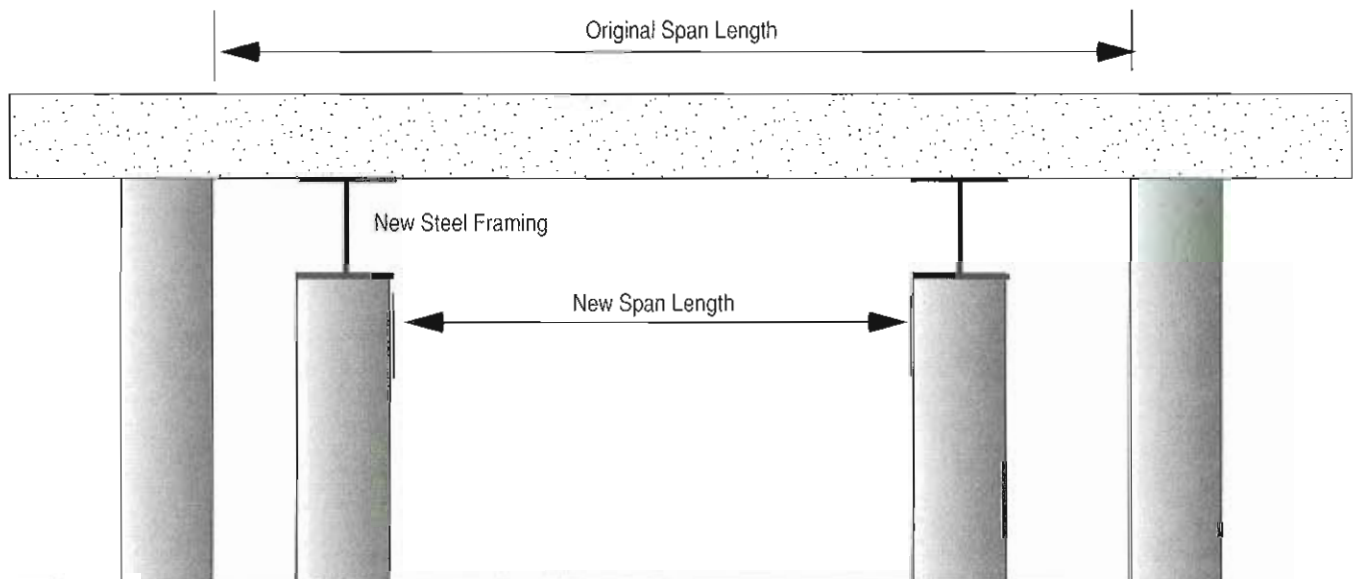
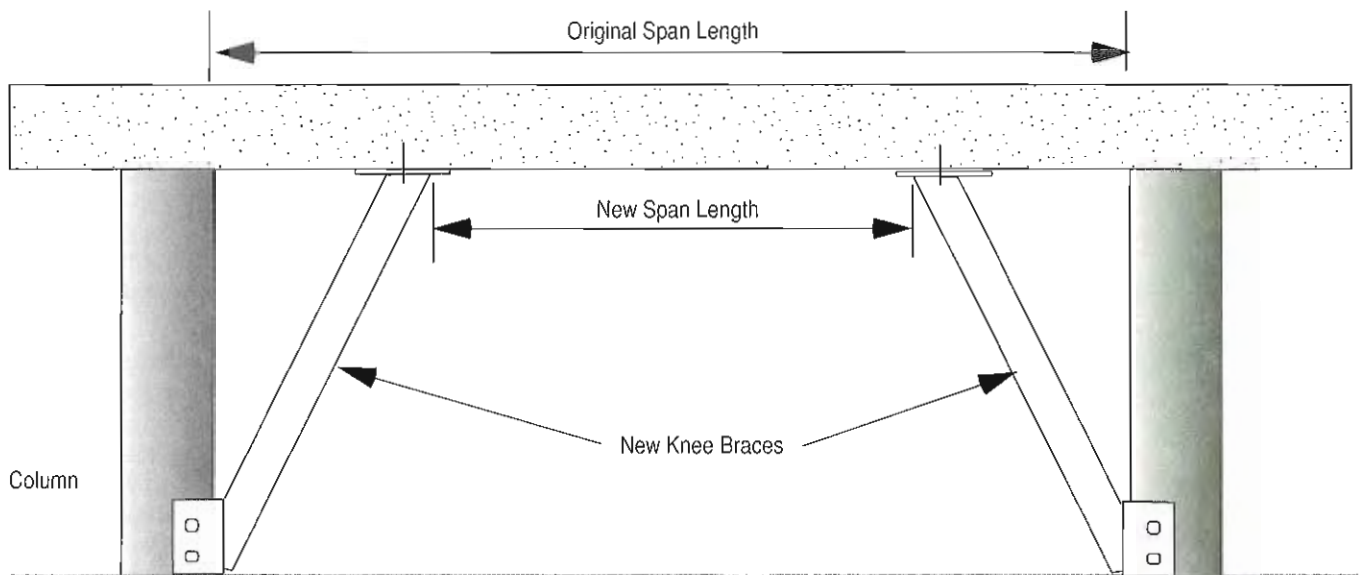
Protection of externally mounted strands and bars against fire and aggressive agents is provided by either precast concrete or shotcrete encasement, or by large grouted strand ducts.



Span Shortening Techniques

Span length shortening, adding additional flexural capacity or stiffness, can be very cost effective. Span shortening for slabs and beams is accomplished

by various methods, including enlarging the column capitals, adding steel or concrete diagonal braces, or placing subframing within the span.

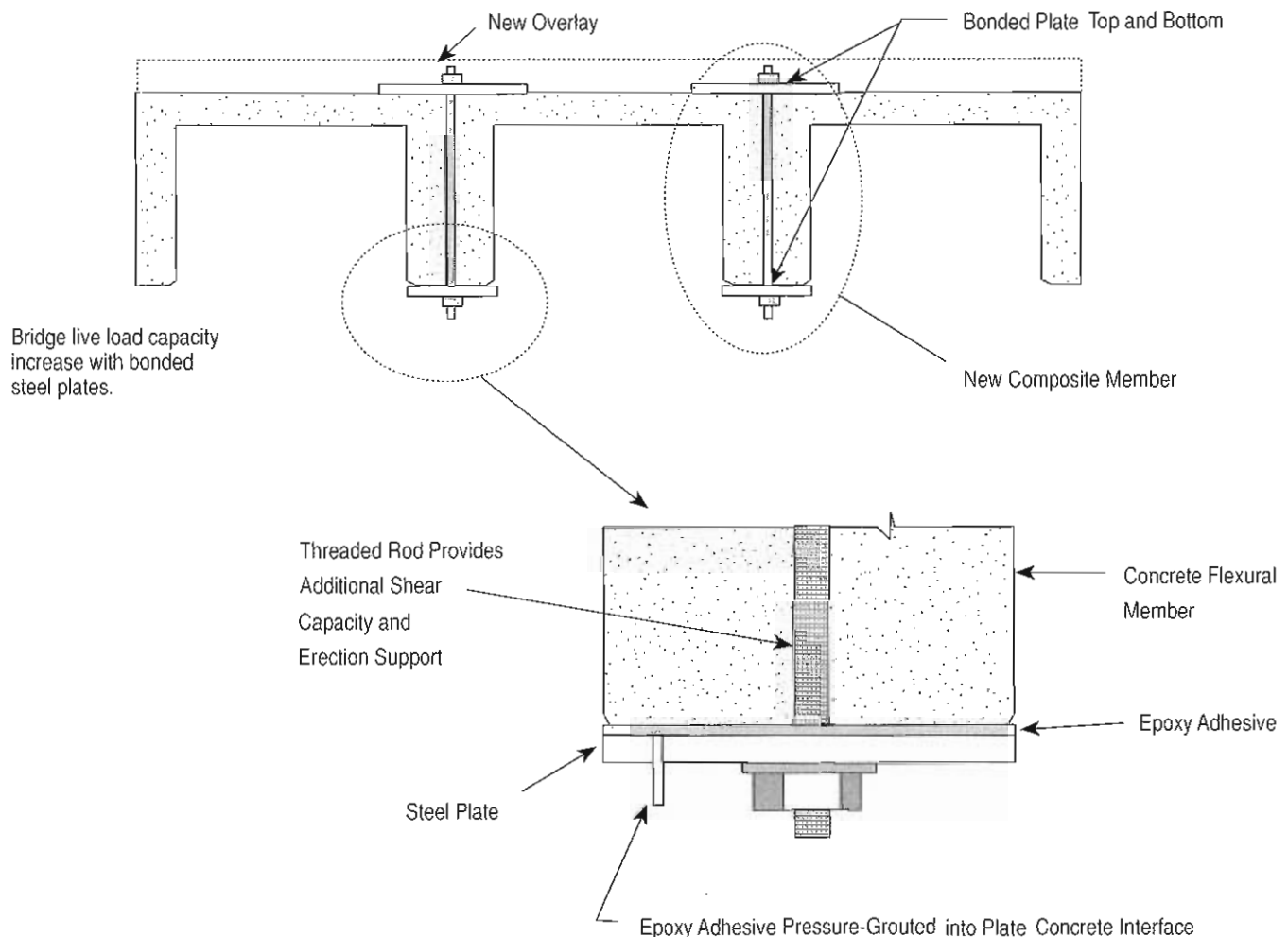


Bonded Steel Plate Reinforcement

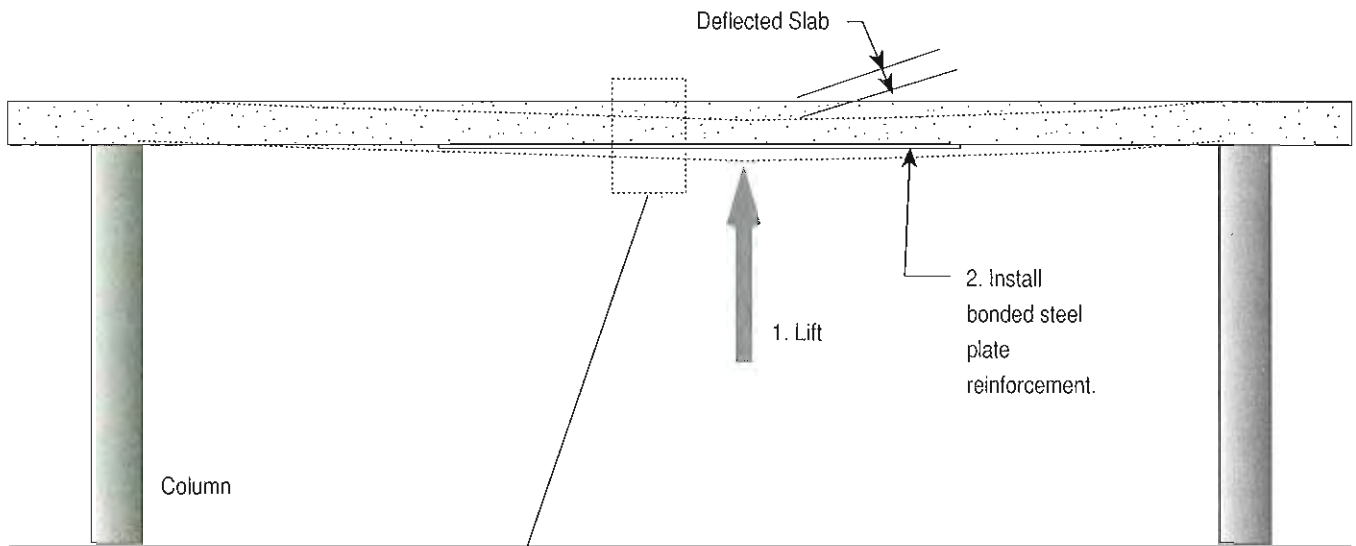
Externally bonded reinforcement is an effective method of increasing live load capacity or removing unwanted deflection. In most cases, steel plates are bonded, using epoxy, to the soffit or sides of flexural members. An advantage of this technique is that repair results in only a small increase in dimensions, which may be important for vertical traffic clearance or aesthetics.

The reinforcement can only be stressed by the application of live loads, or if the flexural member is jacked, prior to installation of the bonded reinforcement. When using steel plates, removal of *mill scale* and

any bond-inhibiting materials is required. Shot blasting or heavy abrasive blasting produces a rough surface on the steel, which improves the adhesive bond and shear transfer. Mating concrete surfaces, heavy abrasive blasting is required. Effective bonding has been achieved using either pressure-injected flowable epoxy resin or epoxy gel applied to the mating surfaces prior to final erection of the steel plates. In some applications, expansion anchors are used in combination with the epoxy adhesive to develop adequate shear transfer between the concrete and steel.

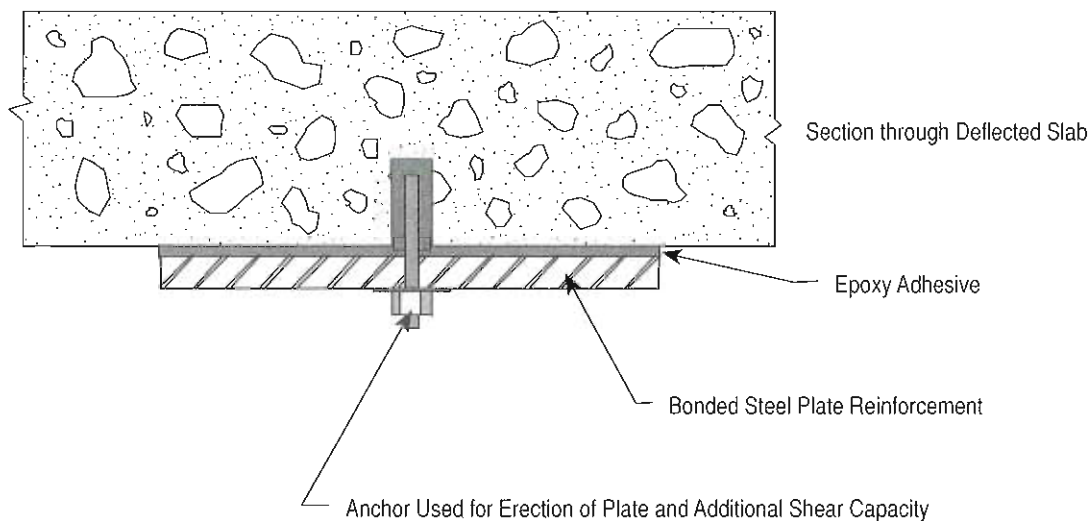


Correction of Deflected Member with Bonded Steel Plate



Procedure for Correcting Deflected Slab

1. Lift slab to design position, or slightly above.
2. Install new bonded reinforcement to slab soffit.
3. Release temporary shoring.
4. Loads are transferred to new bonded reinforcement, and deflection is controlled.

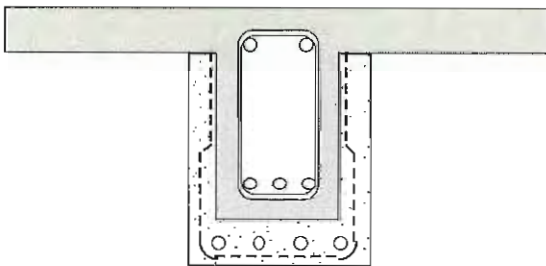


Concrete Overlay and Section Enlargement

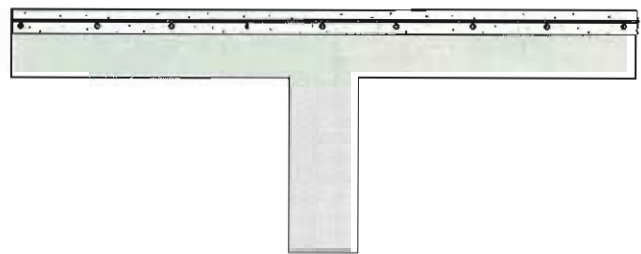
Concrete overlaying techniques have been effective when used to increase both flexural capacity and the stiffness of concrete floor slabs and beams. This technique involves the addition of considerable dead load, thus requiring

careful analysis of its effects on the supporting structural components. Slabs can be overlaid from the top side or soffit. When soffit overlays are constructed, shotcrete or form and pump techniques must be used.

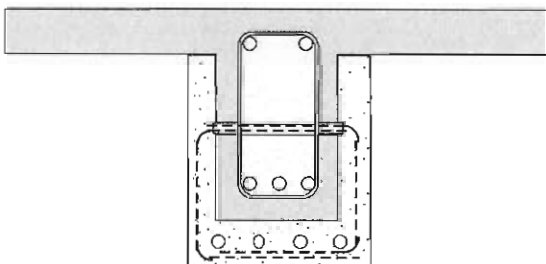
Beam Overlay



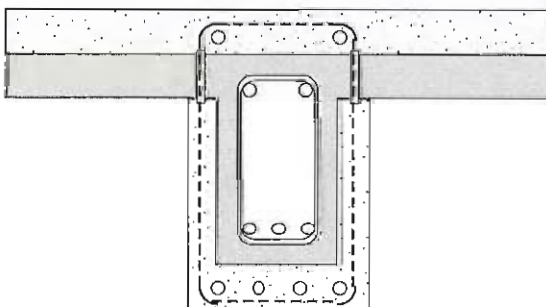
Overlay on Top of Slab



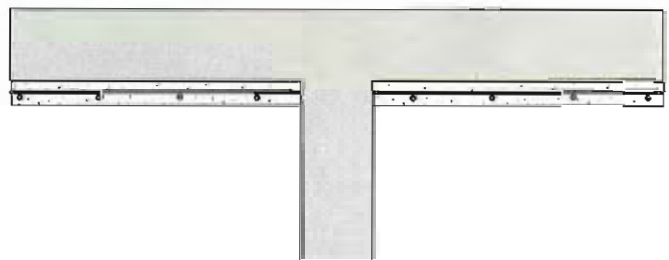
Beam Overlay



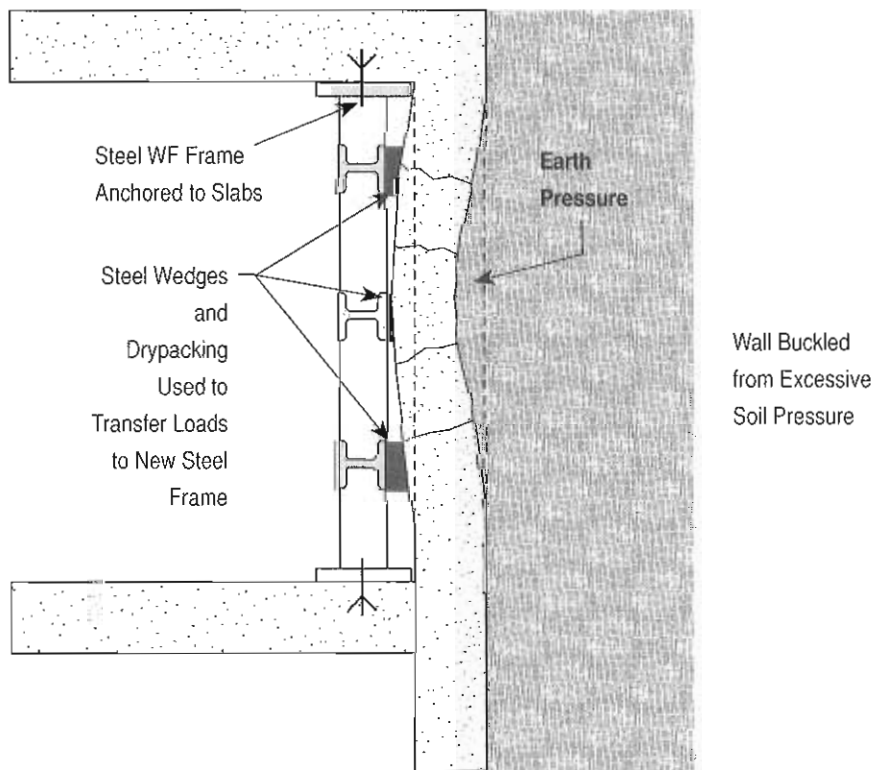
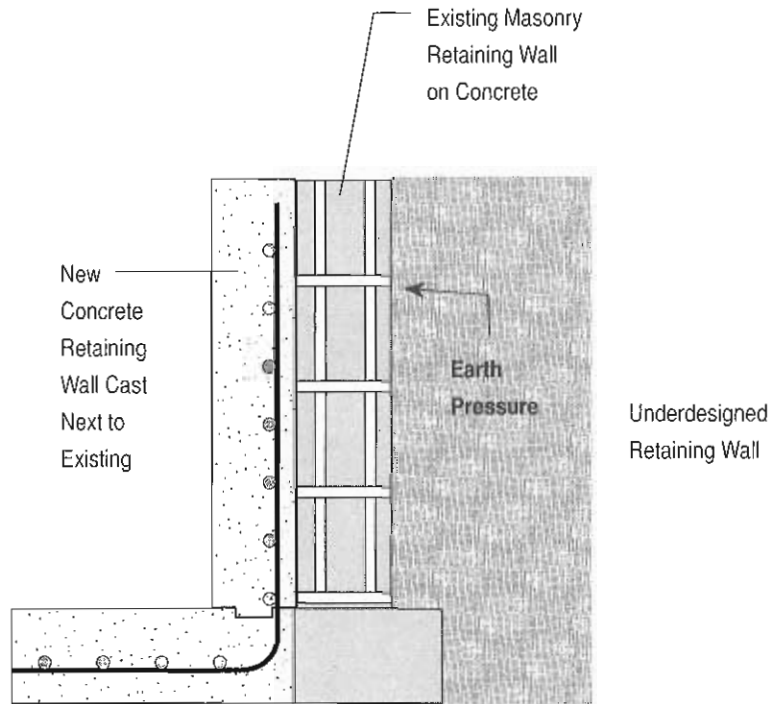
Combination Slab and Beam Overlay



Soffit Slab Overlay



Wall Strengthening

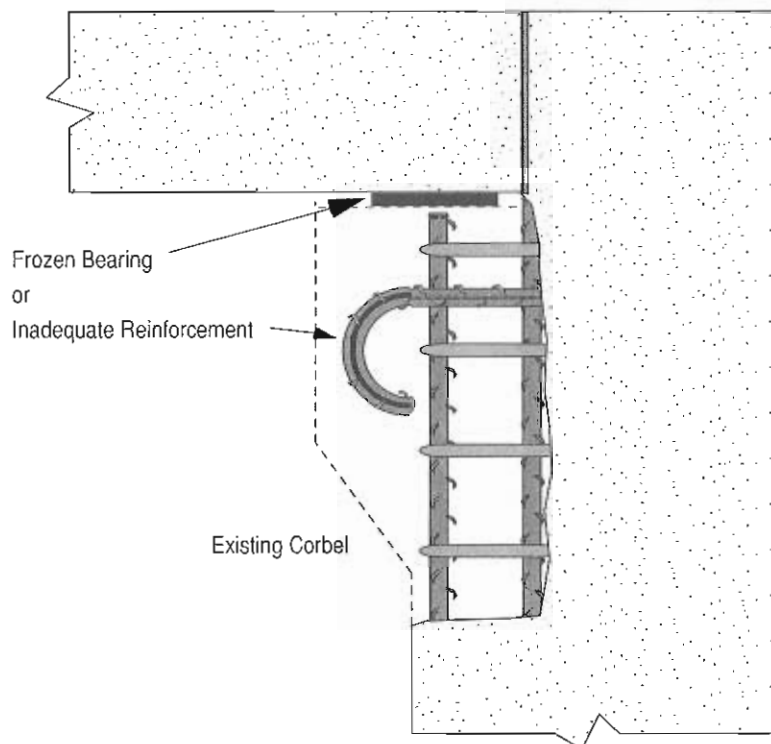


Section 7: Connection Stabilization and Strengthening

The following topics are covered in this section:

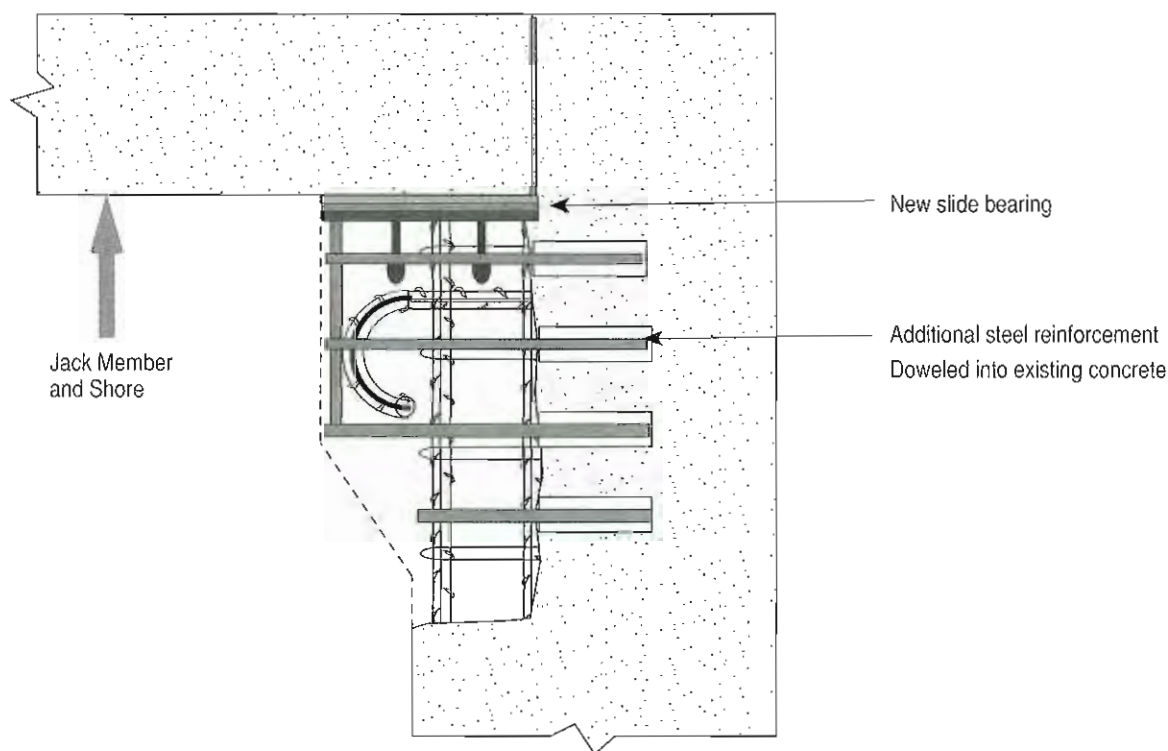
Reconstruction of Corbel Bearing
Externally Mounted Compression Struts
Externally Mounted Bearing Assembly

Reconstruction of Underdesigned or Nonfunctioning Corbel

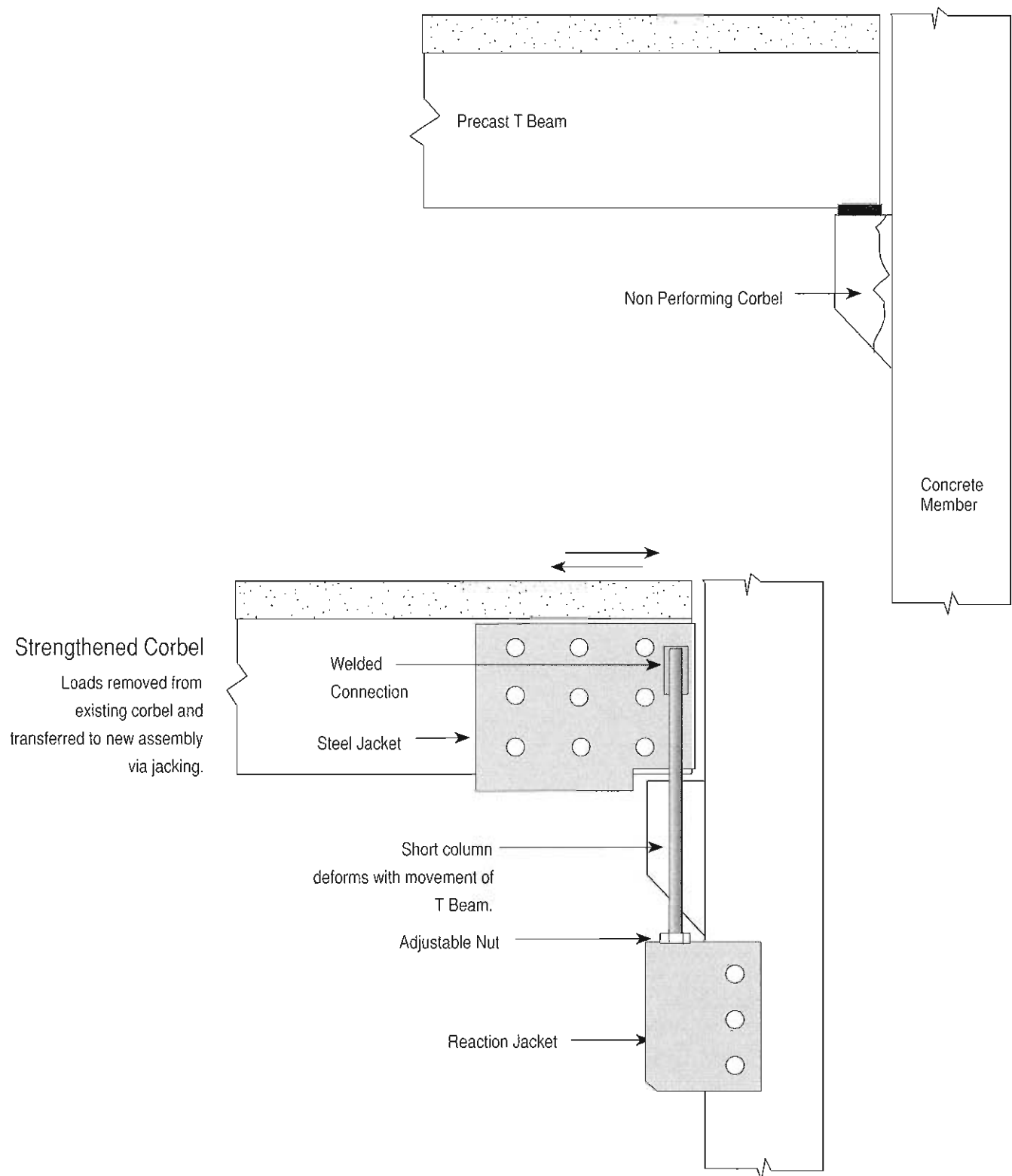


Several joints exist within structures, including those at beam-column connections. These connections must be free to rotate, expand, and contract. If the connection fails to allow for these movements, or the structural support elements become overstressed, reconstruction becomes necessary. Various techniques are available for this reconstruction, including:

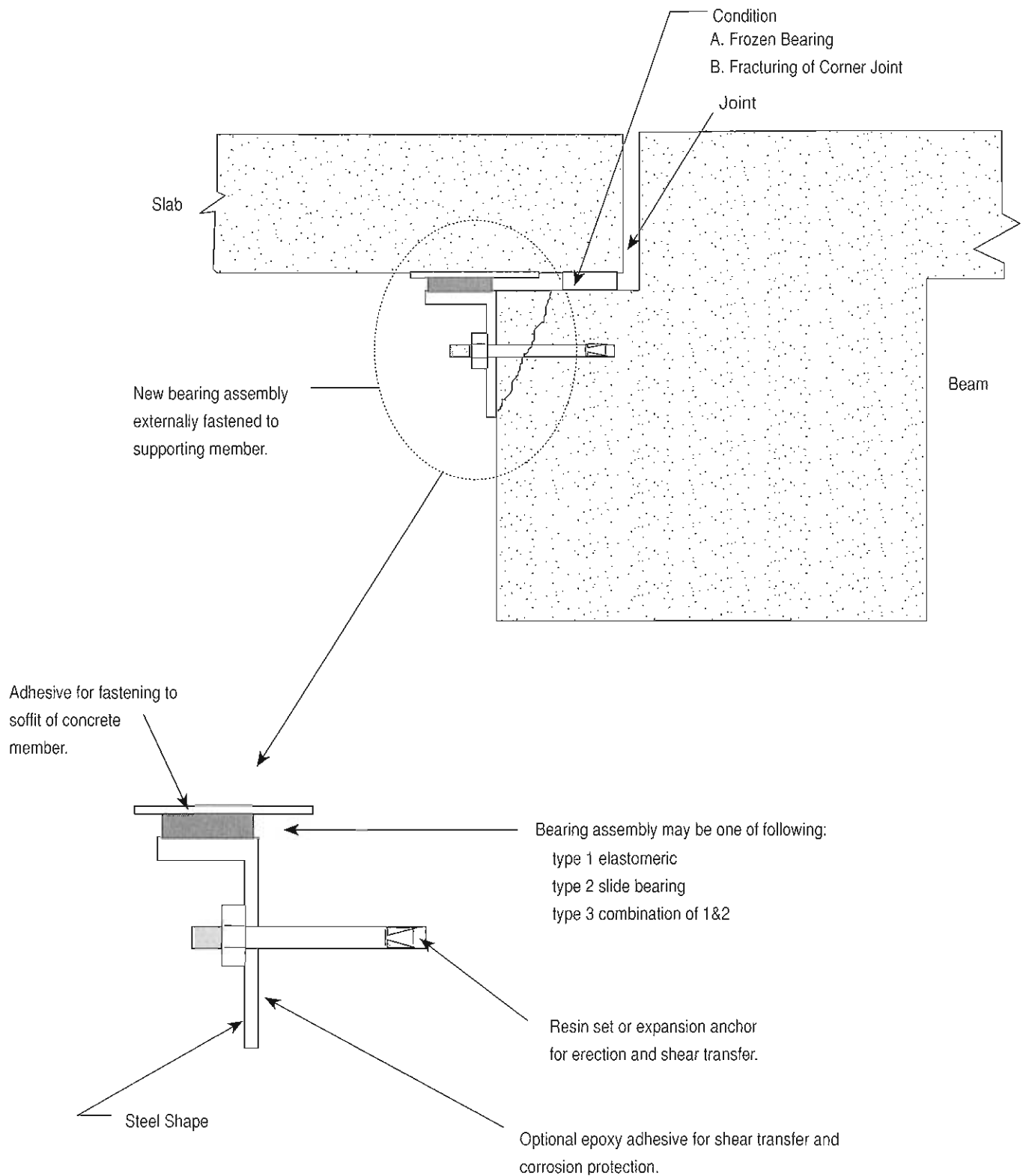
- corbel reconstruction
- short compression column (pedestal)
- tension strut hanger
- shear shelf



Externally Mounted Compression Struts



Externally Mounted Bearing Assembly



Section 8: Crack Stabilization

The following topics are covered in this section:

Performance Requirements for
Crack Repairs

Understanding Crack Movements

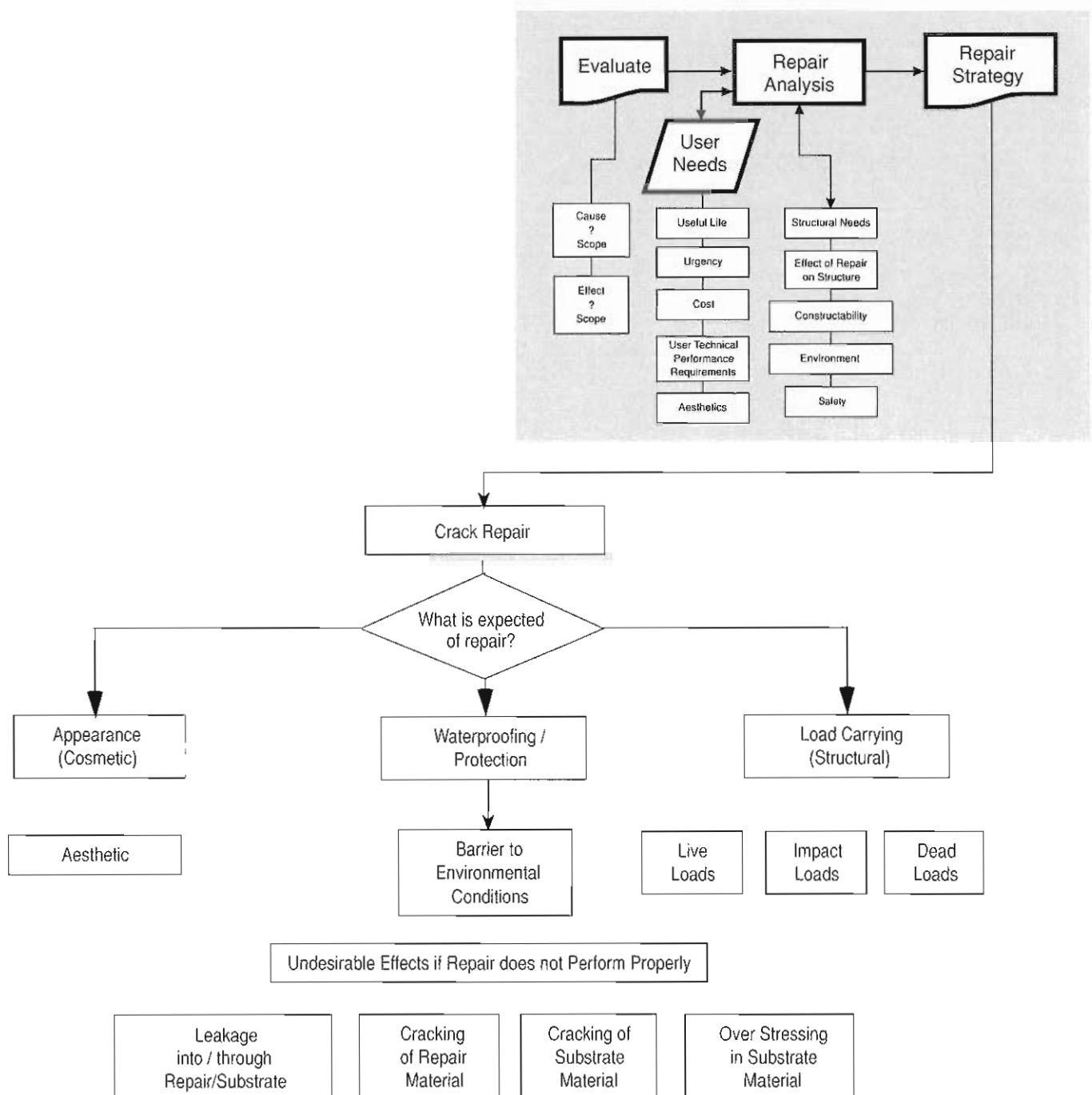
Cause/Effect Design Errors

QualityControl

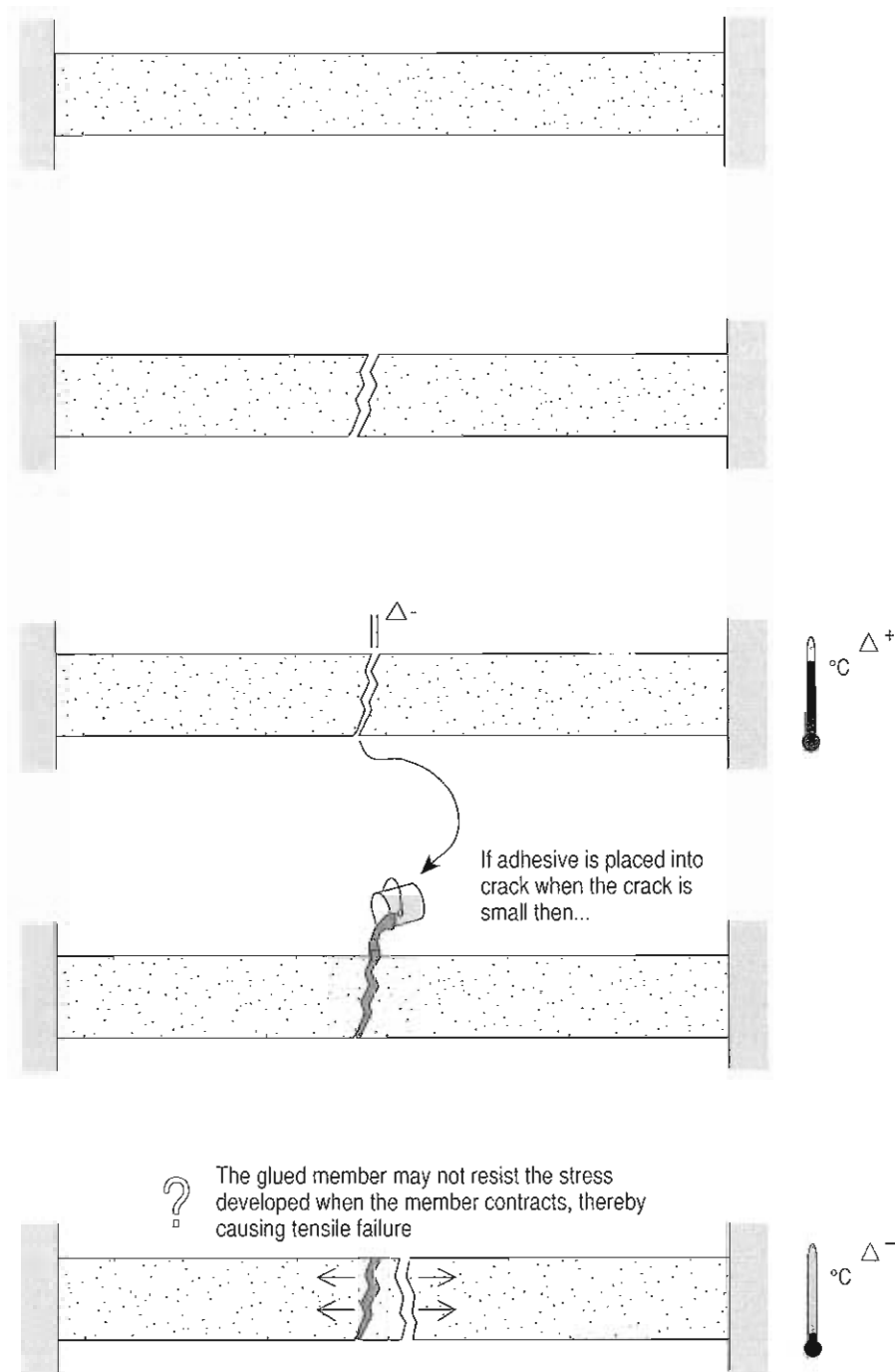
Techniques for Placing Adhesives into
Fractured Concrete

Performance Requirements for Crack Repairs

There are a variety of crack repair techniques presently available. To properly design a particular repair, performance requirements should be clearly understood.

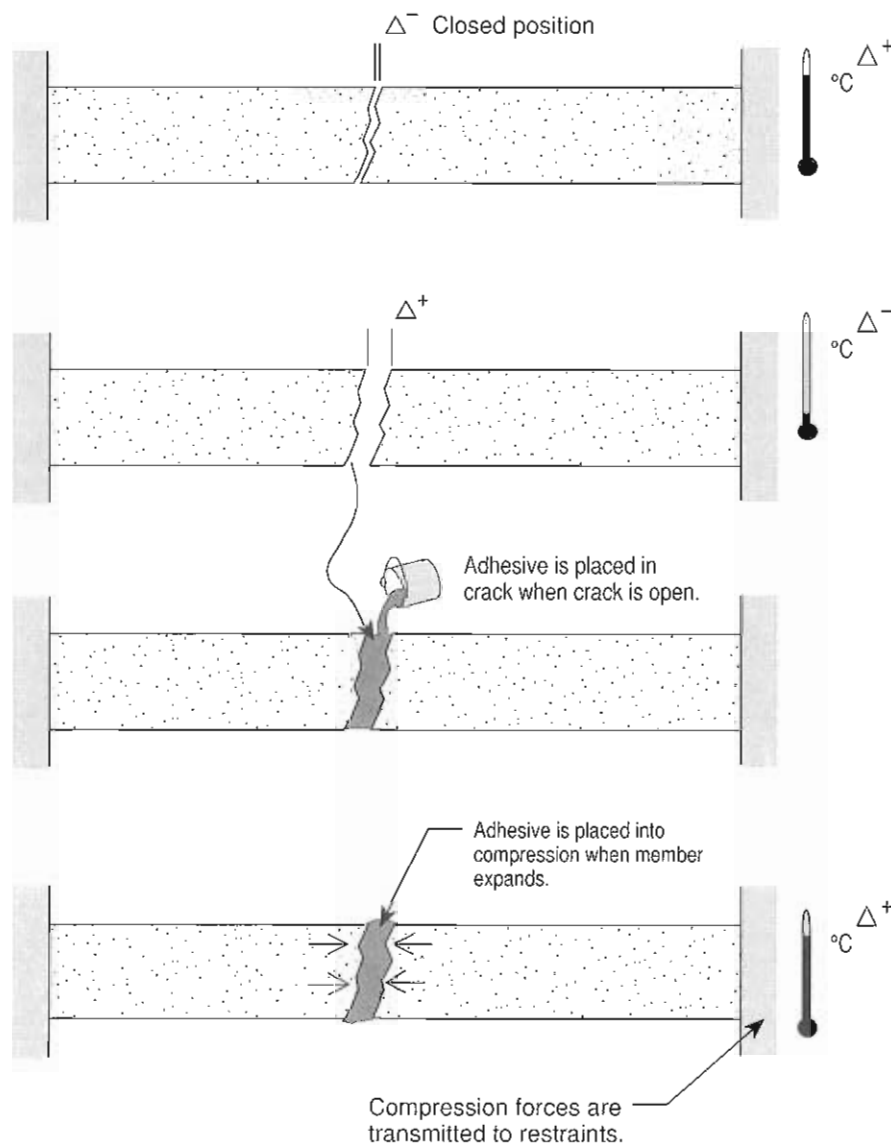


Understanding Crack Movements



There are a variety of techniques available to solve problems caused by concrete cracks. Cracking may cause loss of structural load transfer, provide a conduit for aggressive liquids and gases into and through the member, and/or create an aesthetic problem. The following discussion addresses structural crack repair when crack movement is a factor. A common method of repairing cracks to restore structural load transfer and provide waterproofing is the placement of polymer materials into the fracture plane. The repair may, or may not, be successful, depending on many factors.

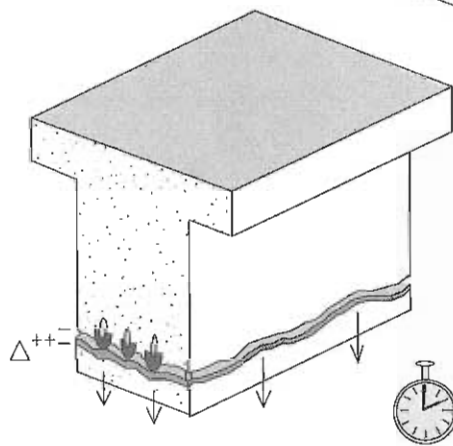
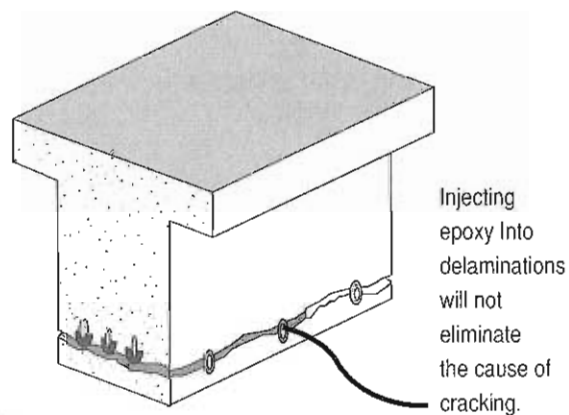
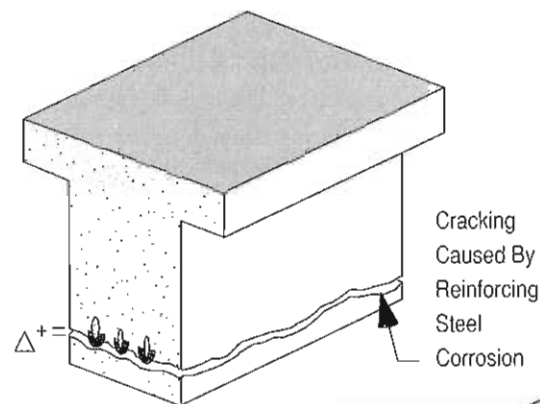
Liquid adhesives such as epoxy, polyester, acrylic are most commonly used for restoring load transfer. These adhesives become solid, and their placement in the fracture plane may alter the structure's behavior. Crack formation may have many causes (Part One, "Concrete Behavior"), but after the crack forms, its behavior may not be related to the original cause of the crack.



The sequence on the left details the formation of a crack. Crack behavior (movement) may be affected by temperature, loads, moisture and other factors. Most cracks move! It is important to understanding crack movement prior to designing crack repairs. If polymer adhesive is used, it will attempt to glue the fracture and prevent any movement within the fracture plane. The cause, amount, and timing of movement will dictate whether the repair will perform as intended. A successful repair will result in movement being either absorbed as internal stress or moved to another, controlled location. The repair may fail as a result of faulty evaluation, design, material selection, methods, or workmanship.

Note: Liquid adhesives which become solids behave similarly inside cracks, regardless of their elongation capabilities outside of the crack. Their behavior is one of a rigid material not allowing any elastic stretch. Materials can only stretch or elongate when allowed to deform. In a small sample, a material with good elongation is free to "neck down" under tension or "bunch up" when compressed. In a fracture plane, the material has no place to "neck down" or "bunch up." Only materials with a cellular structure (with gas pockets) are allowed to deform within a fracture plane.

Cause/Effect Design Errors



Corrosion
continues,
causes
re-cracking
and
delamination.

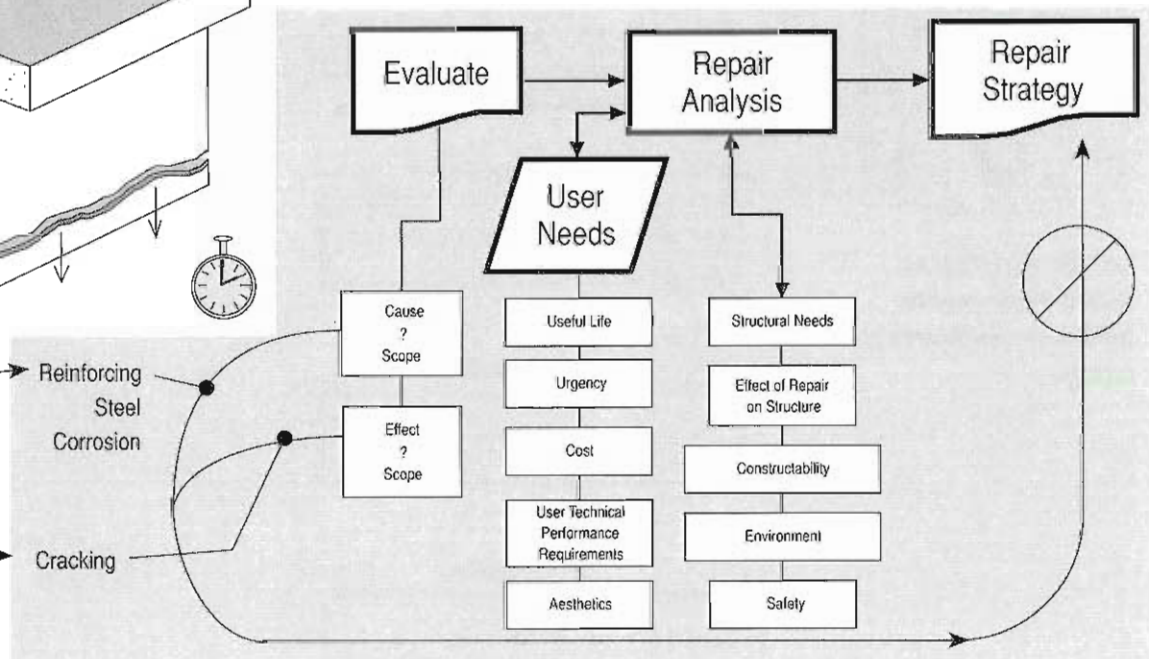
Reinforcing
Steel
Corrosion

Cracking

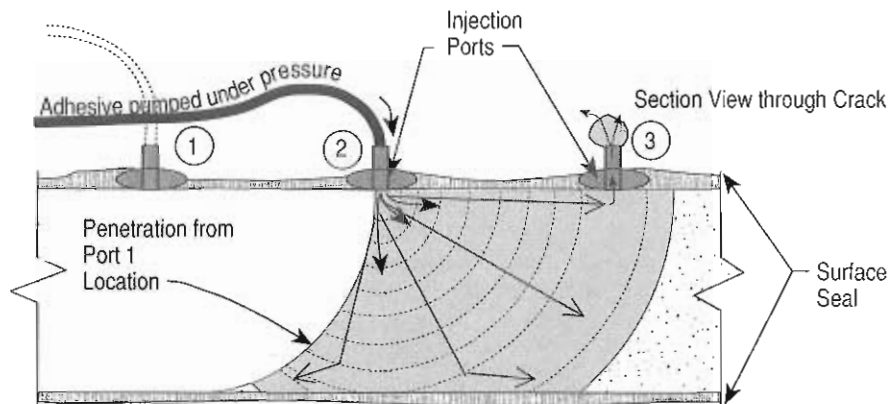
This text block provides a summary of the process shown in the diagrams. It states that corrosion continues, causing re-cracking and delamination. It also identifies the specific components involved: Reinforcing Steel Corrosion and Cracking.

Epoxy Injection of Corrosion Induced Cracks

A common mistake made in the repair of cracks caused by rebar corrosion is the use of epoxy pressure injection. A number of repair jobs, where epoxy resin is pressure-injected into these cracks to reglue the pieces, have been attempted in the past. Very few of these repair jobs proved to solve the problem, because the corrosion process continues, causing additional growth of corrosion products and formation of new cracks. The most appropriate repair solution for corrosion-induced cracking is the removal of concrete over and around corroded bars and treatment by one of the surface repair and protection methods.



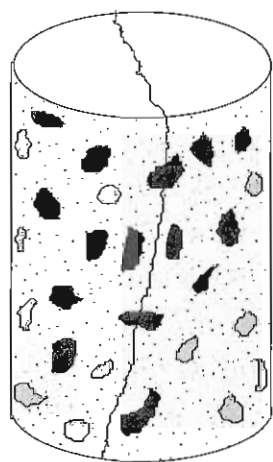
Quality Control



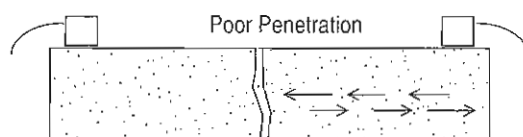
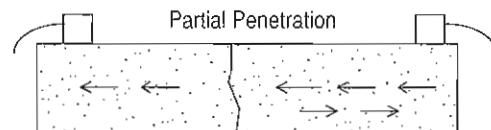
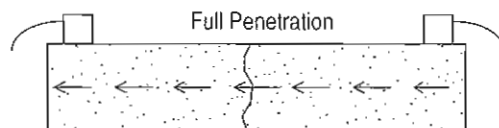
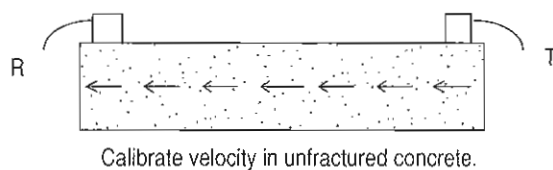
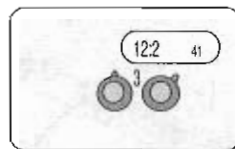
Surface mounted port injection typical flow paths of injected adhesive. Injection begins at location 1. Injection continues until adhesive flows from location 2. After air and debris is free from the flow at location 2, location 1 injection is discontinued and injection is restarted at location 2. The process is continued until the fracture is filled. (Port to Port method)

Rebonding of Fractured Concrete Using Adhesive

Pulse velocity measurements provide a quick and effective quality assurance method for determining penetration of the adhesive into the fracture. The velocity meter is calibrated on a non-fractured section of concrete. The transmitter and receiver are fixed at a constant distance apart. Properly injected fractures and nonfractured concrete have similar transit times. Locations along the fracture, where the epoxy has not penetrated, exhibit longer transit times.



Core specimen of injected fracture. Visual inspection provides a review of penetration success.

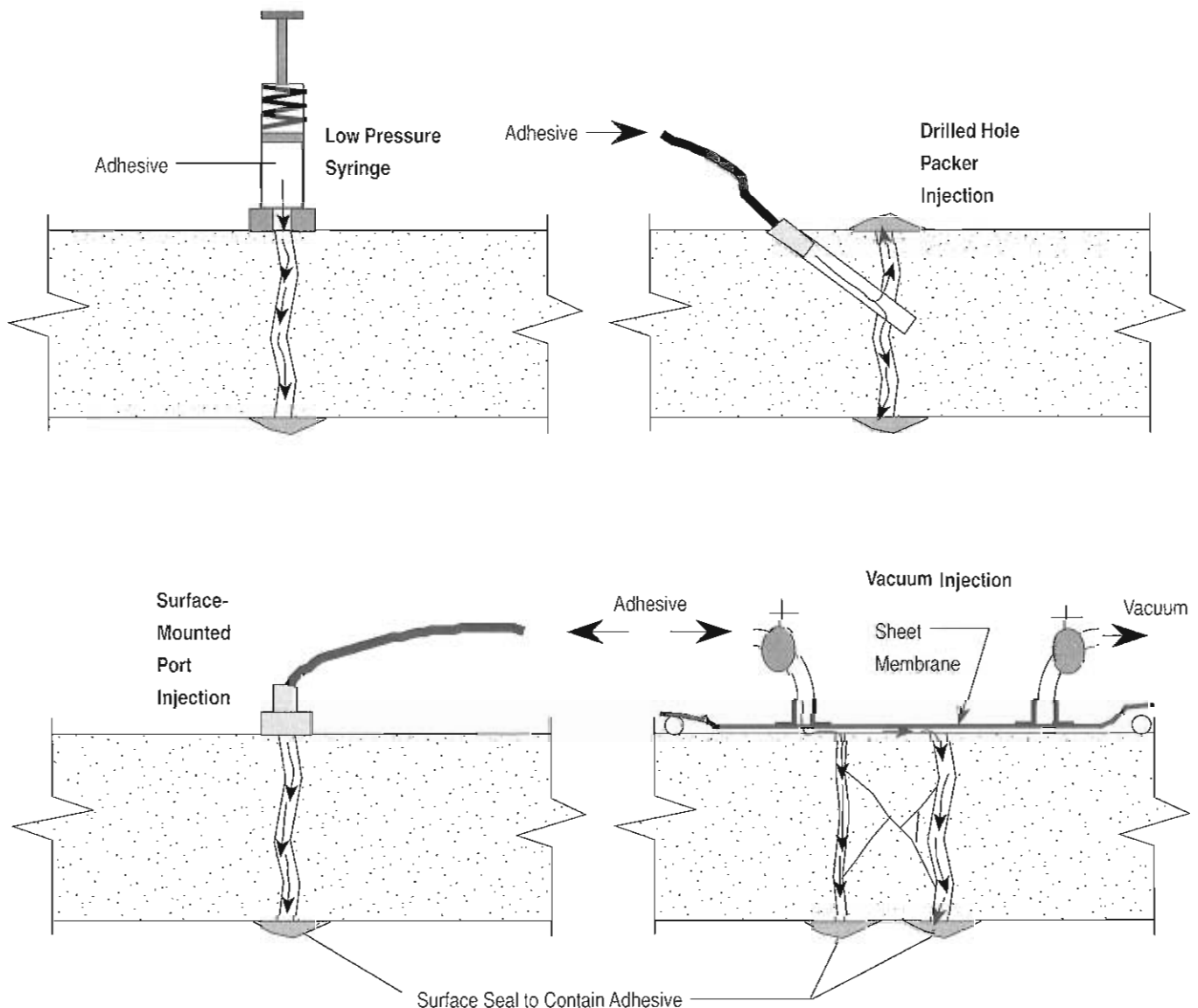


Techniques for Placing Adhesives into Fractured Concrete

Injection grouting of fractured concrete to restore the intended monolithic action is a well-developed repair technique. The most common adhesives for this type of repair are epoxy and methacrylate resins.

Various systems are used to introduce the adhesives into the fractured surface. Cracks 0.002 in. (0.05mm) wide, half the thickness of a human hair, have been successfully injected.

The best method of determining whether one system works better than another is to measure the in-place penetration and bond of the adhesive. Core testing and the use of pulse velocity measurements (see Part Two: Concrete Evaluation) are useful tools when monitoring performance objectives.



Additional Sources of Information

Johnson, S.M., Deterioration, Maintenance, and Repair of Structures, McGraw-Hill Book Co., New York, 1965.

Klaiber, F.W., et al, Methods of Strengthening Existing Highway Bridges, NCHRP Report 293, 1987, Washington, D.C.

Part Five **Protection**

Part Five

Protection

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Introduction to Part Five

Concrete structures are subject to many conditions that may adversely affect their expected performance. Understanding the relationship between, premature or unexpected deterioration or user dysfunction, and the causes of these performance issues, provides a basis for selecting methods of protection. Protection is a method of controlling the cause of deterioration or user dysfunction by:

1. altering the service or exposure conditions,
2. enhancing the physical properties of the concrete to better resist the exposure or service conditions,
3. installing a barrier between the service/exposure condition and the susceptible concrete, or
4. altering the electro-chemical behavior when corrosion of embedded metal is a factor.

Protection methods that address deterioration issues are generally intended to extend duration between maintenance cycles. For example, concrete spalling is a form of deterioration that may be caused by an exposure/service condition which promotes reinforcing steel corrosion. Protection of the concrete from the exposure/service condition may be accomplished by utilizing sealers, membranes, coatings, or surfacing. Protection methods that address user dysfunction are intended

to correct conditions that are adversely affecting the use of the structure. Leakage of ground water through a crack into occupied space is an example of user dysfunction. Protection of the occupied space from the unwanted water is accomplished with various protection methods such as grouting, diversion, membrane waterproofing, or rout and seal.

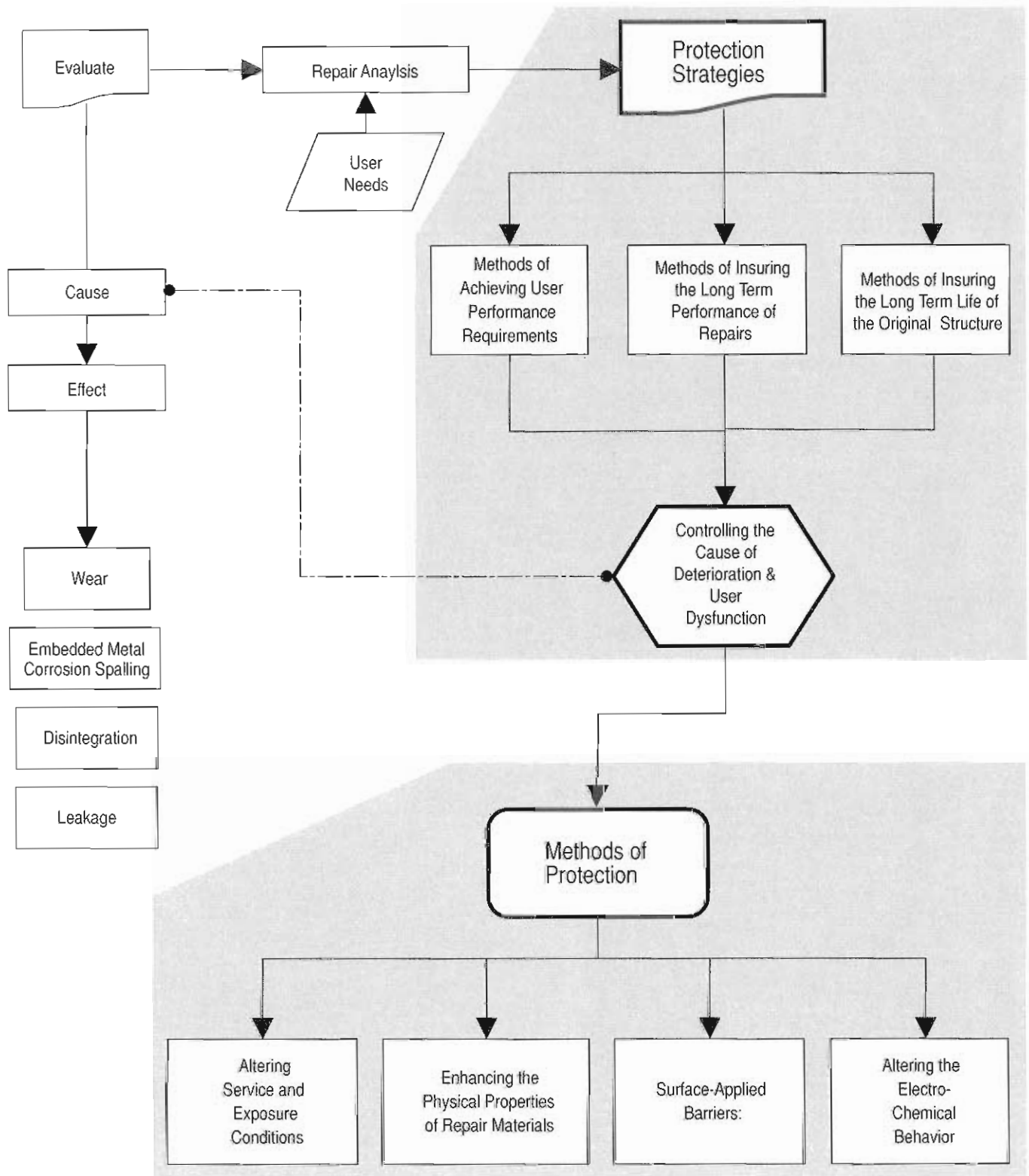
Protection technology is rapidly expanding, providing not only new insights into causes and effects, but also new strategies and materials. The technology is, however, not without risk, due to the lack of long term performance histories: therefore, results may be disappointing. Where no long term history of use is available, a pilot project may be appropriate.

This section begins with a summary of common deterioration and user dysfunction effects, with various protection strategies that may be employed. Section 2 describes specific protection techniques such as coatings, grouting, and joint seals.

Section 1: Strategies

The following topics are covered in this section:

Introduction to Strategies
Controlling Chloride-Induced Corrosion—New Concrete
Controlling Chloride-Induced Corrosion—Existing Concrete
Controlling Chloride-Induced Corrosion in Cracks and Construction Joints
Controlling Carbonation-Induced Corrosion
Controlling Aggressive Chemical Surface Damage
Controlling Freeze-Thaw Damage
Controlling Freeze-Thaw Damage Behind Surface Repairs
Controlling Water Flow Through Structures
Controlling Water Leakage Through Plaza Deck Systems



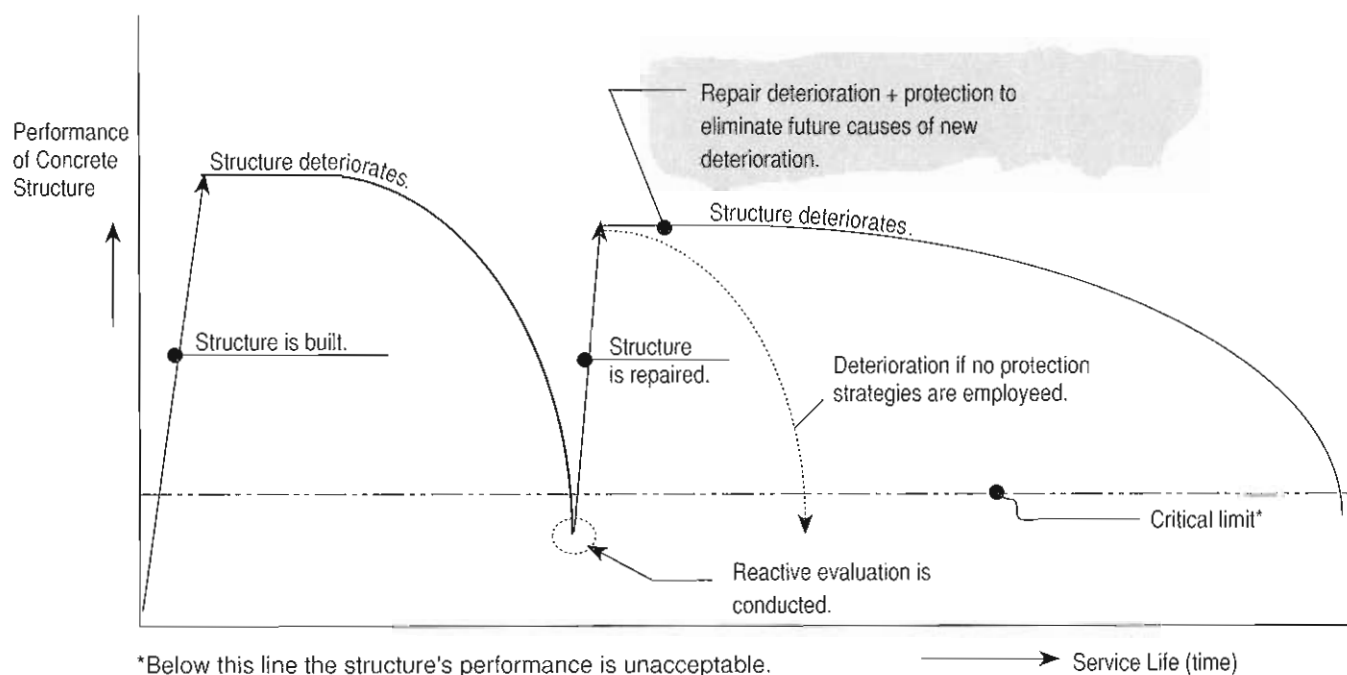
Introduction to Strategies

There are numerous methods and techniques available to protect concrete. Choosing the appropriate technique for a given condition requires an evaluation of the various strategies. Such items as useful life, cost effectiveness, redundancy, constructibility, environment and aesthetics must be considered.

Protection systems can be installed at the time of construction or at any time during the life of the structure. Good design practice for new construction provides for anticipated protection needs. For example, installing a membrane waterproofing system on the below-grade portion of a concrete foundation wall is a protection strategy

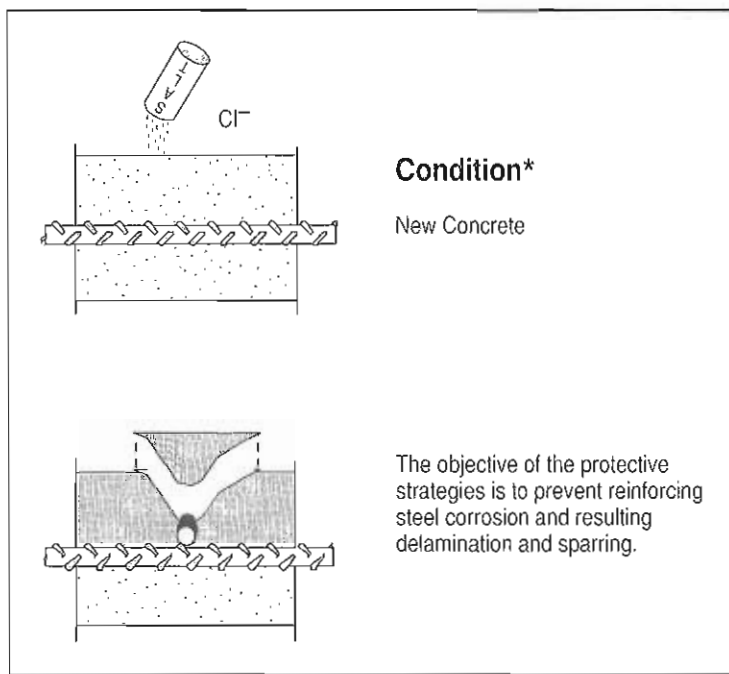
that anticipates the possibility of water leakage through cracks or high permeability concrete within the wall. Many conditions that affect deterioration or user dysfunction and are not addressed at the time of construction will require repair and/or protection during the life of the structure. Protection of existing structures is generally more difficult and allows fewer options than protection of new structures.

Cost effective protection methods to minimize premature deterioration are designed to offer a favorable cost-benefit to the owner, as compared to no protection at all. Present value analysis is used to determine the cost effectiveness of various strategies.



*Below this line the structure's performance is unacceptable.

Strategies for Controlling Chloride-Induced Corrosion—New Concrete



Condition—New Concrete

The objective of protective strategies is to prevent reinforcing steel corrosion and resulting cracking, delamination and spalling of concrete.

Strategy

Protecting the reinforcing steel from corrosion is a direct way of addressing the corrosive effects of chlorides. Fusion-bonded epoxy coatings (Fig. E) are the most common coating system. There is a controversy associated with this strategy involving the amount of tolerable coating defects and how aggressive a chloride environment can be vs. how many years the protection will last. Another approach to direct control of chloride induced corrosion is demonstrated in Fig. F. Admixtures are available which fight off damaging chlorides. Calcium nitrite is the most common corrosion inhibiting admixture.

New concrete structures can be protected from the effects of chlorides by a number of proven strategies. Fig. A presents the use of low permeability concrete which can be obtained by using low water-cement ratios and special additives, such as micro-silica. Increasing good quality concrete cover also delays chloride-induced corrosion.

Fig. B presents an approach used on many bridge decks. The strategy involves the placing of a low permeability overlay. Materials used for such overlays include micro-silica modified concrete, low water-cement ratio concrete, and latex-modified concrete.

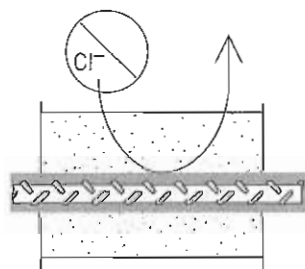


figure e- fusion-bonded epoxy bar coating

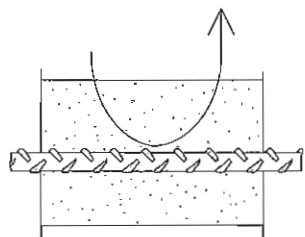


figure f- corrosion inhibitor admixture

*Refer to section on Concrete Behavior-Embedded metal chloride penetration corrosion

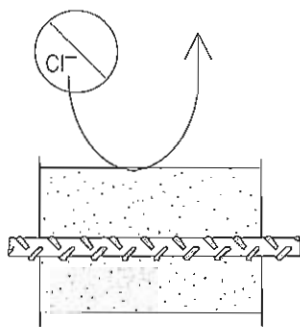


figure a
Low permeability
concrete

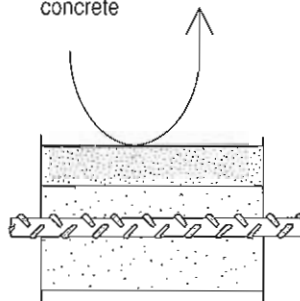


figure b
Low permeability
overlay

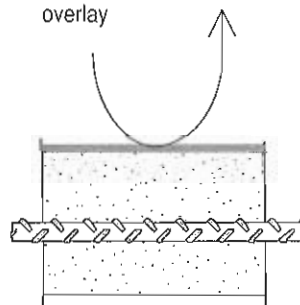


figure j- surface-applied
film building coating /
membrane

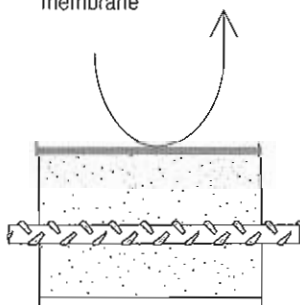


figure k- surface-applied
penetrating sealer

Strategy, continued

Surface applied penetrating sealers and coatings/membranes (Figs. J & K) are proven methods of minimizing the intrusion of chlorides in concrete.

Sealers (impregnates) that screen chlorides include:

- silane based
- siloxane based

Coatings and membranes that screen chlorides include:

- epoxies
- urethanes
- chlorinated rubber
- methacrylates

Strategies for Controlling Chloride-Induced Corrosion—Existing Concrete

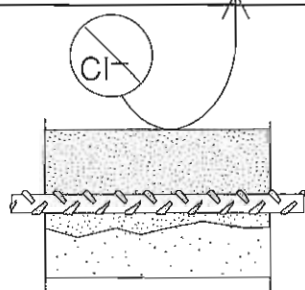
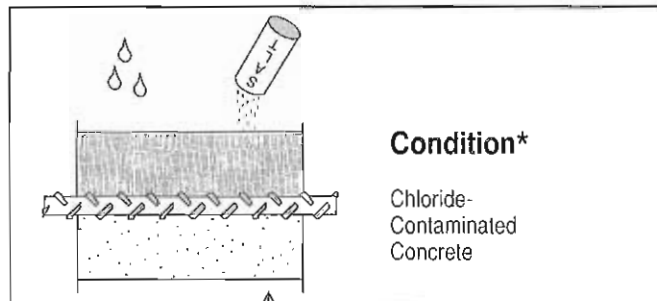


figure l- surface removal of contaminated concrete followed by replacement of low permeability concrete

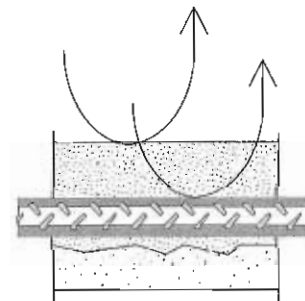


figure m- reinforcing steel protection with removal/replacement of contaminated concrete

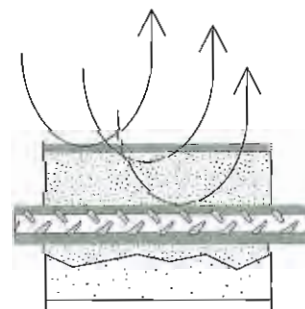


figure n- surface sealer, bar protection, removal/replacement of contaminated concrete

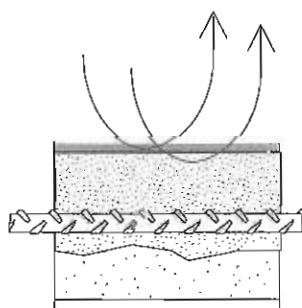


figure o- surface sealer and removal/replacement of contaminated concrete

Strategy

A direct approach is the removal of chloride-contaminated concrete, followed by replacement with low permeability concrete (Fig. l).

Coatings, membranes, sealers and reinforcing steel protection methods can be used in conjunction with the concrete replacement for additional protection (Figs. M, N, O).

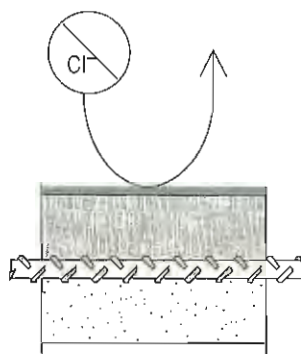


figure c
surface-applied sealer

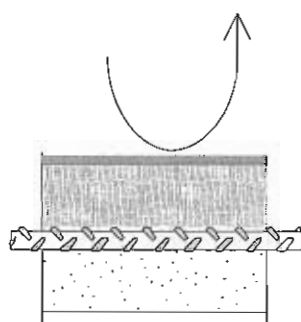


figure d
surface-applied
coating/membrane

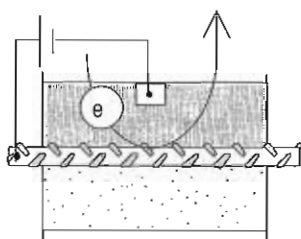


figure g- impressed current
cathodic protection, top
side

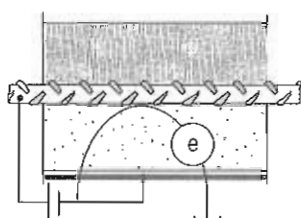


figure h- impressed current
cathodic protection, bottom
side

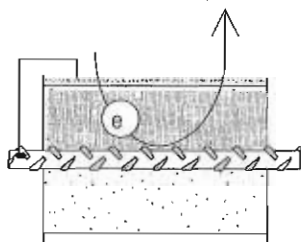


figure i- sacrificial anode
cathodic protection

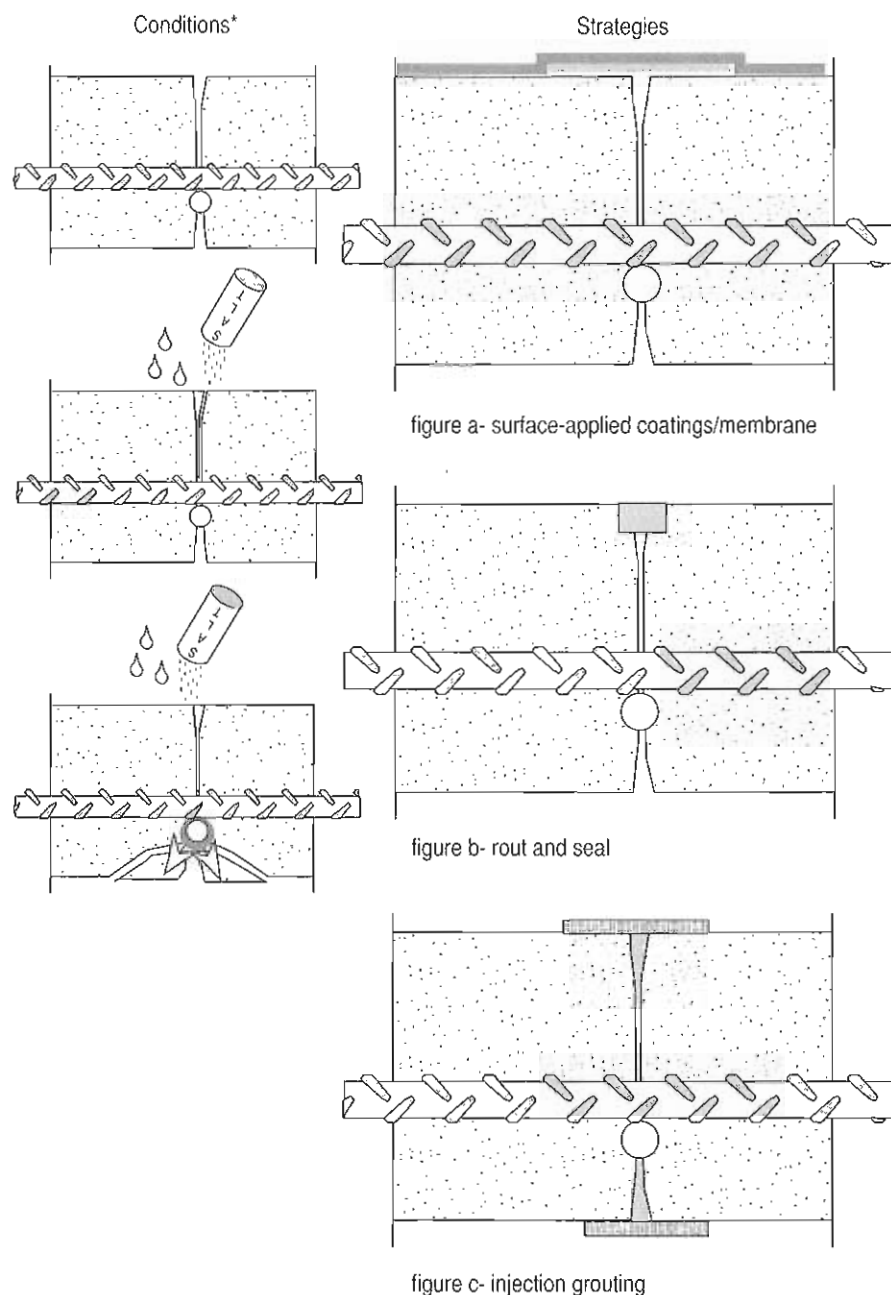
Strategy, continued

Surface applied penetrating sealers (Fig. C) have become a common strategy used to minimize chloride penetration into existing concrete. Sealers allow free flow of moisture vapor in and out of the affected concrete. The concrete's internal moisture level equalizes with the surrounding environment. In some cases, the moisture level will be higher because of the effects chlorides have on absorbing moisture.

Surface applied film-building coatings and membranes (Fig. D) are more positive barrier systems than sealers to the ingress of chlorides and moisture absorption. Coatings and membranes have very low vapor transmission capabilities and, therefore, limit the concrete's ability to breathe. Caution should be exercised when completely encapsulating a concrete structure or its elements.

Cathodic protection systems utilizing impressed currents and surface-mounted anodes (Figs. G & H) provide a positive method of controlling the corrosion process. The systems require continual monitoring and adjustment. An alternative to impressed current cathodic protection is the method of surface-applied sacrificial anode (Fig. I). The anode is spray-applied molten zinc which is electrically connected to the reinforcing steel. As the zinc fights off corrosion, it "sacrifices" itself, eventually disappearing.

Strategies for Controlling Rebar Corrosion in Cracks and Construction Joints



Controlling corrosion of embedded reinforcing steel at cracks and construction joints requires the cut-off of chlorides to the reinforcement. There are three strategies illustrated here which accomplish the cut-off of chlorides.

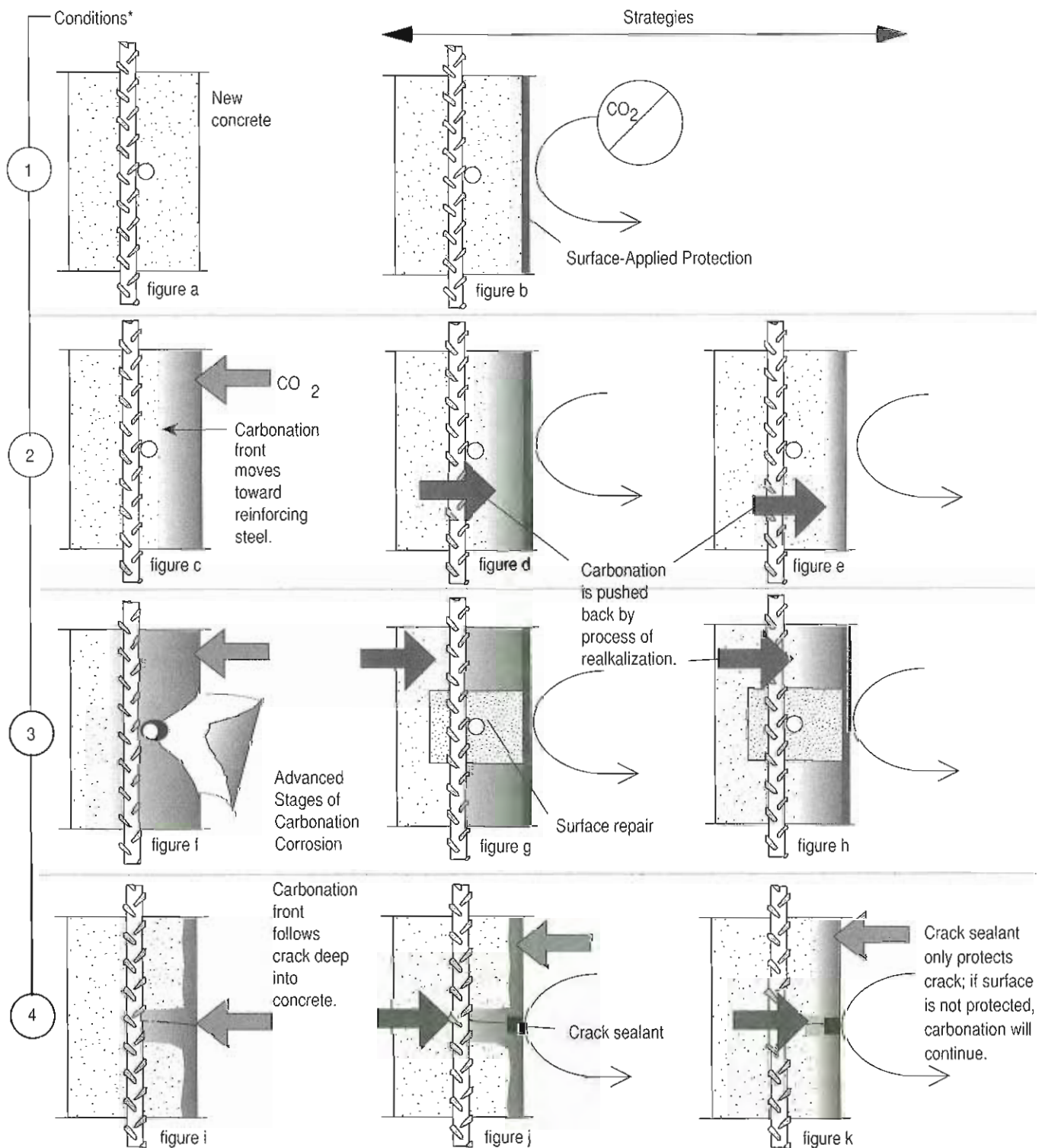
Fig. A utilizes a surface-applied coating or membrane. The physical properties of the coating/membrane system are dependent upon the amount of crack/joint movement and the service conditions. Traffic bearing elastomeric systems are commonly used in parking structures.

A simple and effective method of minimizing chloride penetration (through cracks) to the reinforcement is the use of an elastomeric joint sealant placed in a cut recess (Fig. B). The method is known as *rout and seal*. Rout and seal is often used in conjunction with a membrane or coating system.

Another method used to protect embedded reinforcement is injection grouting (Fig. C). Injection grouting fills the crack with a sealant (epoxy, polyester, methacrylate, urethane). The success of a grouting method depends largely on how well the sealant bonds to the crack surface and how much movement the crack/joint can accommodate without causing failure in the sealant or adjacent concrete. See the section on crack stabilization for more detailed discussion.

*Refer to Section on Concrete Behavior—Embedded Metal Corrosion—Carbonation

Strategies for Controlling Carbonation-Induced Corrosion



*Refer to Section on Concrete Behavior- Embedded Metal Corrosion-Carbonation.

Strategies for Controlling Carbonation

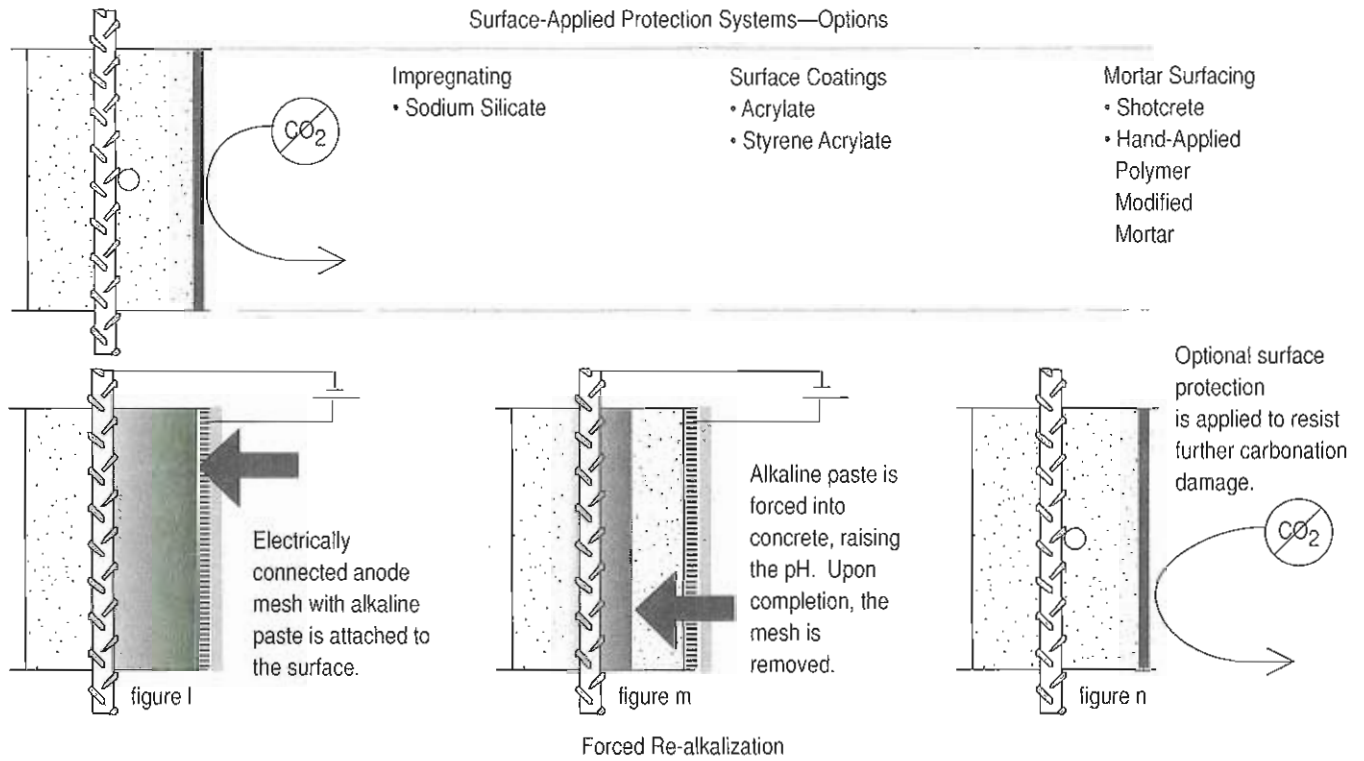
Carbonation is a condition within concrete that allows corrosion of embedded reinforcing steel to occur when moisture and oxygen are present. The reaction of carbonation occurs through exposure of the concrete to acidic gases (Fig. C). Low permeability concrete (Fig. A) is all that is generally required to resist carbonation. Extra protection can be obtained by installing a high density, low vapor transmission coating, membrane, or impregnating material. Existing concrete, with significant depths of carbonation (front of carbonation is close to reinforcing steel), can be protected by installing surface barriers (Figs. D, G, J.). Surface applied barriers which have low vapor transmission allow the uncarbonated concrete to re-alkalize (increase pH) the carbonated concrete, pushing the carbonation front back toward the surface.¹

Cracks in concrete (Figs. I, J, K) may allow carbonation to penetrate relatively quickly to the areas around reinforcing steel. Elastomeric membranes (crack bridging) or crack sealants (rout and seal) are strategies that will arrest the carbonation process.

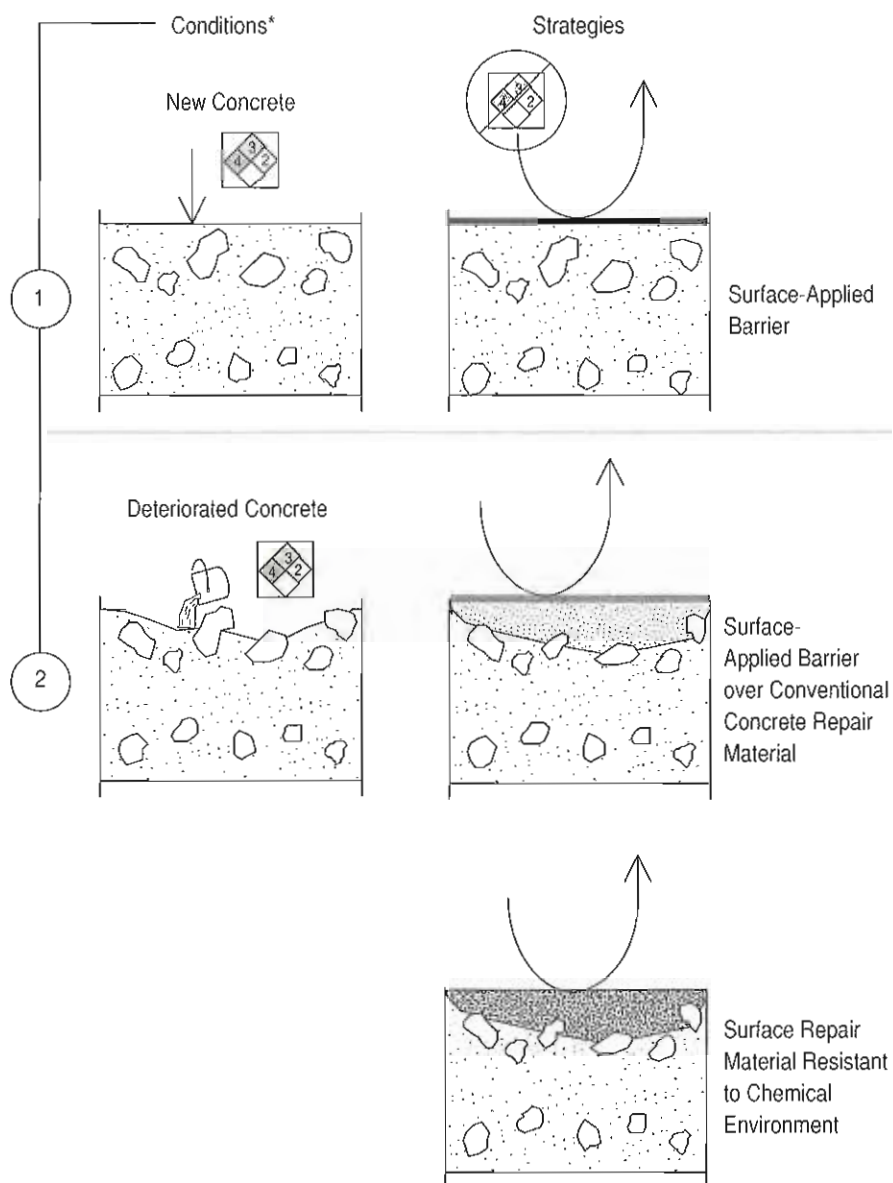
Recent developments in electrochemical technology provide for techniques of transporting alkalis into carbonated concrete (Figs. L, M, N). Alkaline paste is placed on the concrete surface, which contains an electrified grid. (The grid is connected to the reinforcing steel electrically.) A DC current is pumped into the circuit, driving the alkaline paste from the surface into the concrete. It may take a number of days or weeks to complete the process of re-alkalization.¹

¹Bijen, J.M., Maintenance and Repair of Concrete Structures, Instituut TNO voor Bouwmaterialen en Bouwconstructies Delft (Netherlands).

Surface-Applied Protection Systems—Options



Strategies for Controlling Aggressive Chemical Surface Damage



Aggressive chemical attack (liquid or gas) on concrete surfaces can be controlled by using chemically resistant materials in the concrete mix, or using surface-applied barrier coatings, membranes or surfacing systems. Typical protection systems are listed in the accompanying table:

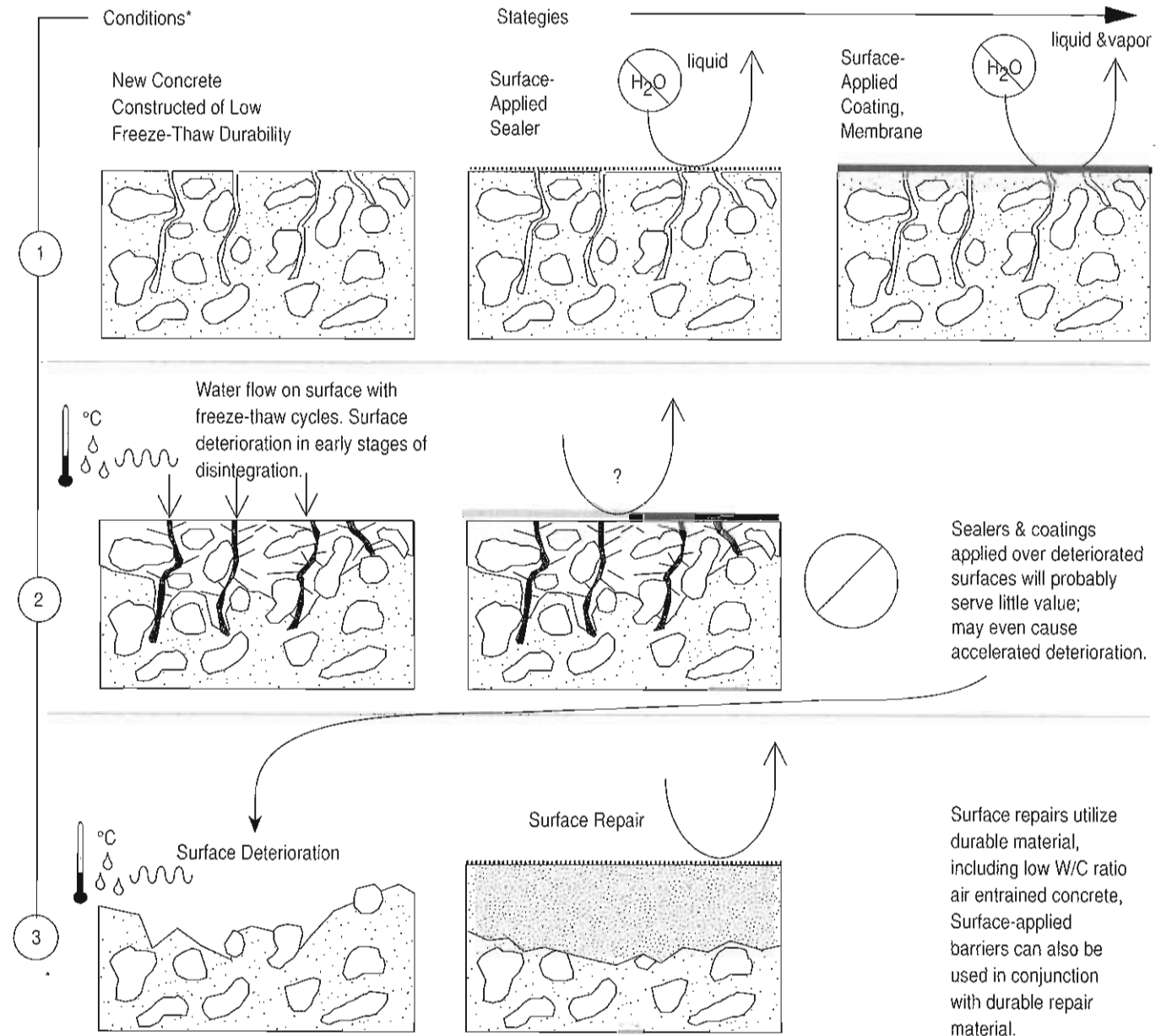
*Refer to Section on Concrete Behavior-Disintegration Mechanisms-Exposure to Aggressive Chemicals.

Type of Surface Protection	Maximum Service Temperature °F/°C	Alkalies		Acids				Solvents		Bleach
				Inorganic	Organic					
		Strong	Weak			Weak	Moderate	Strong	Organic	
Epoxies	150/66	✓	✓		✓	✓		(1)	(1)	✓
Epoxy—Novolac	180/80	✓	✓	✓				✓(2)	✓(2)	
Furans	360/180	✓	✓	✓	✓	✓	✓	✓	✓	
Methacrylates (MMA)			✓		✓			✓(2)	✓(2)	
Polyesters	230/107		✓		✓	✓				✓
Potassium Silicates	2000/1093			✓(3)	✓	✓	✓	(1)	(1)	
Sulfur Cement	190/88			✓(4)	✓	✓				
Urethanes	150–250 66–122	✓	✓	✓(4)	✓	✓				✓
Vinyl Esters	220–250 104–127		✓	✓	✓	✓		✓	✓	
PVC		✓	✓	✓	✓	✓	✓			
Acid Brick	High			✓(3)	✓	✓	✓			
Carbon Brick		✓	✓	✓	✓	✓	✓			

- (1) Resistant only to some solvents
(2) Moderate resistance to solvents
(3) Not resistant to Hydrofluoric Acid (HF)
(4) Moderate resistance to acids

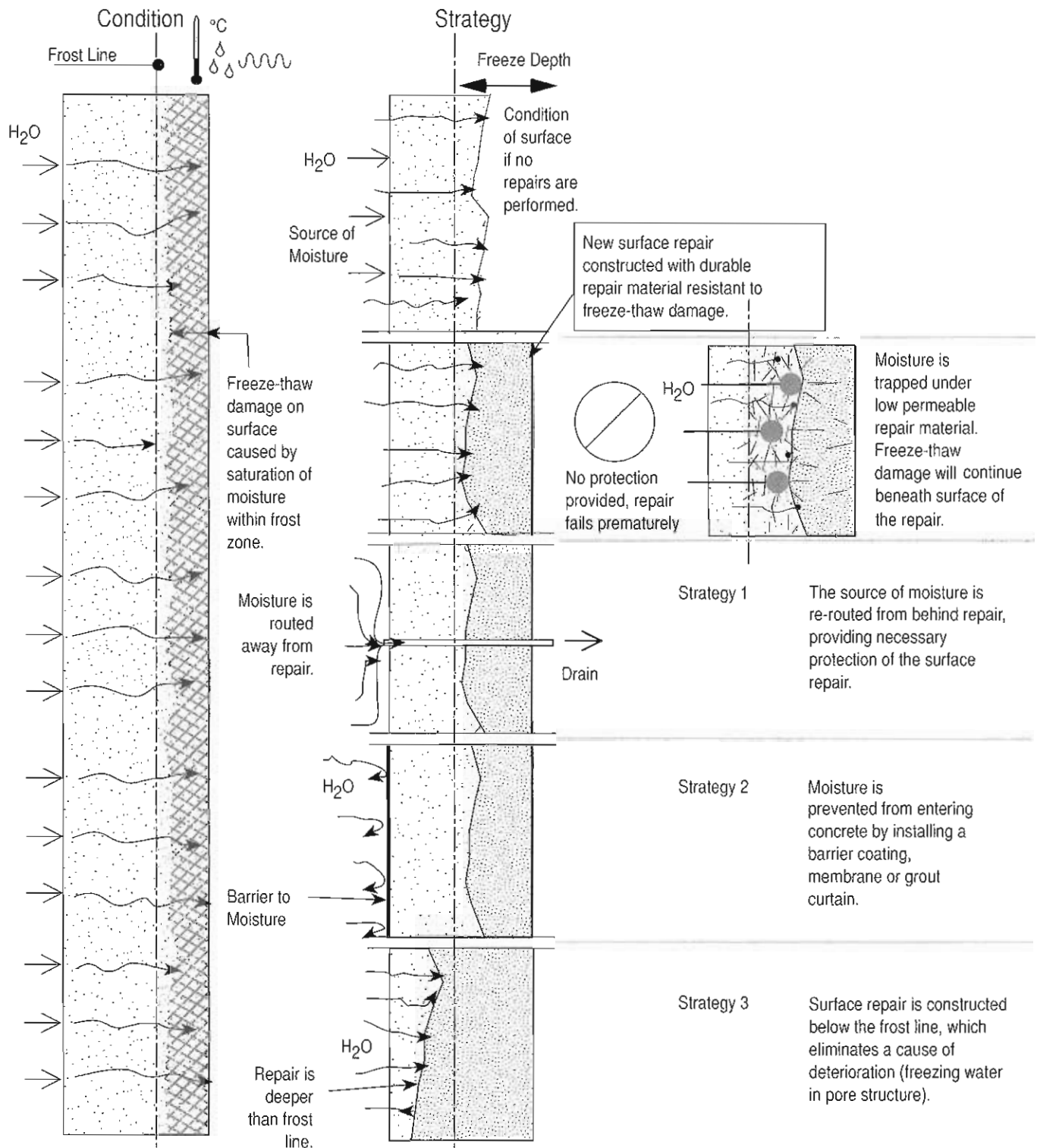
Note: This table should be used as a guide only. Actual performance may differ depending on formulation.

Strategies for Controlling Freeze-Thaw Damage

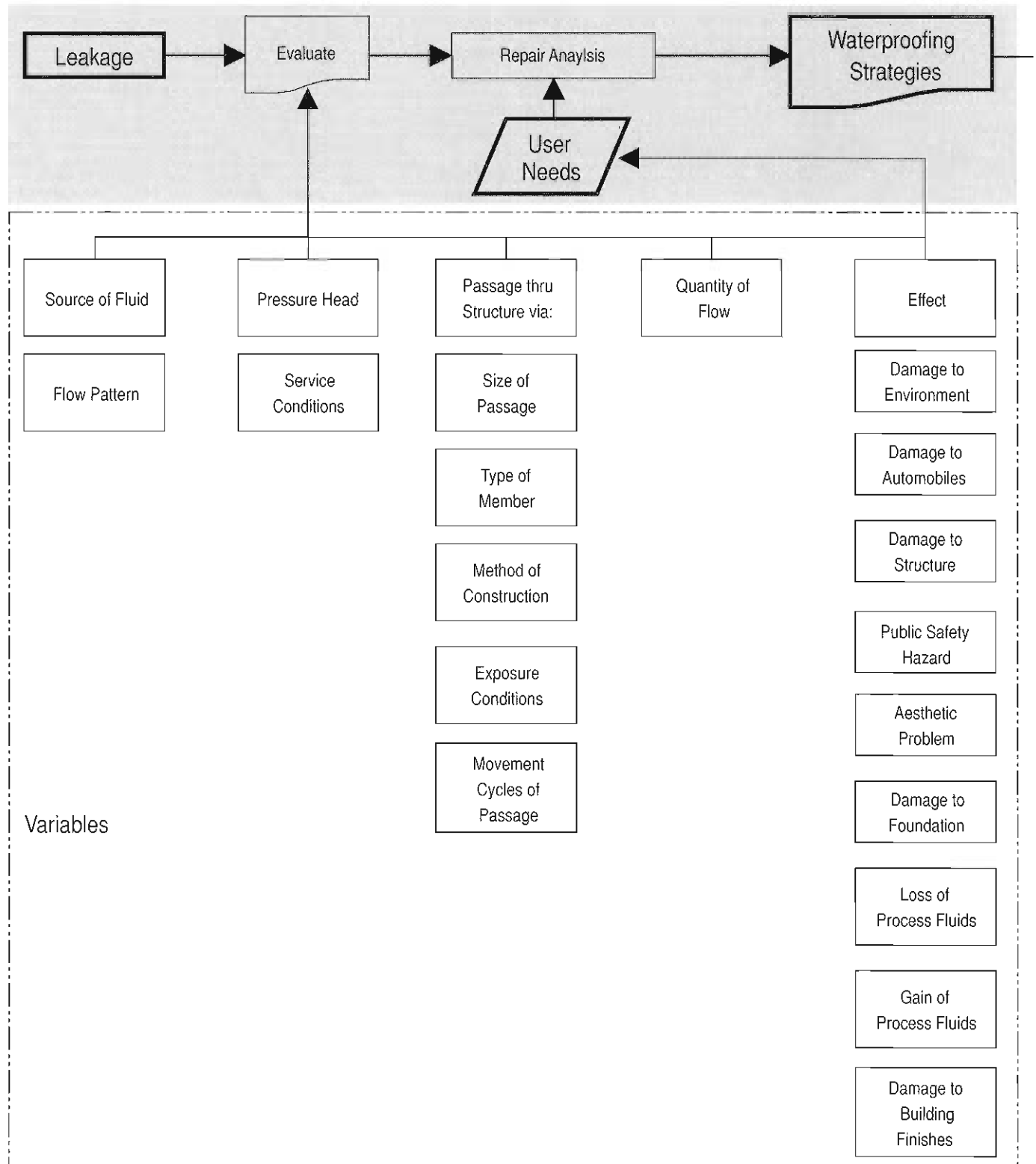


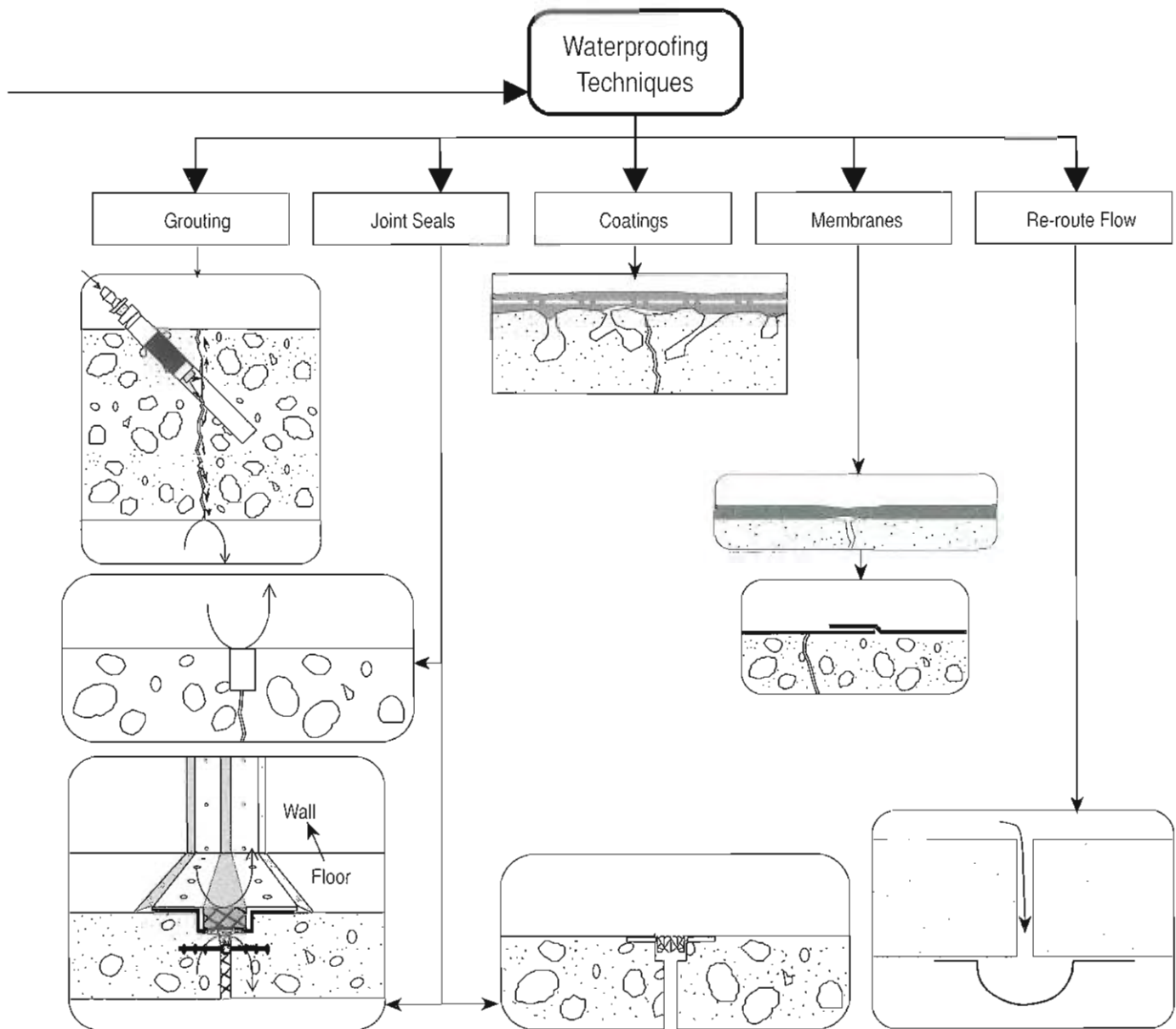
*Refer to Section on Concrete Behavior—Disintegration Mechanisms—Freeze-Thaw Disintegration

Strategies for Controlling Freeze-Thaw Damage Behind Surface Repairs



Strategies for Controlling Water Flow Through Structures





The leakage of water (liquids) through concrete is one of the most troubling user dysfunctions and causes of deterioration. There are numerous variables associated with water flow that should be considered when designing a protection (waterproofing) strategy. The flow chart demonstrates many of the

important variables. Those variables, to a large degree, govern the selection of a repair method. When developing waterproofing strategies, all methods and techniques should be considered, and two or more should be evaluated based on cost, service life, aesthetics, side effects, and constructibility.

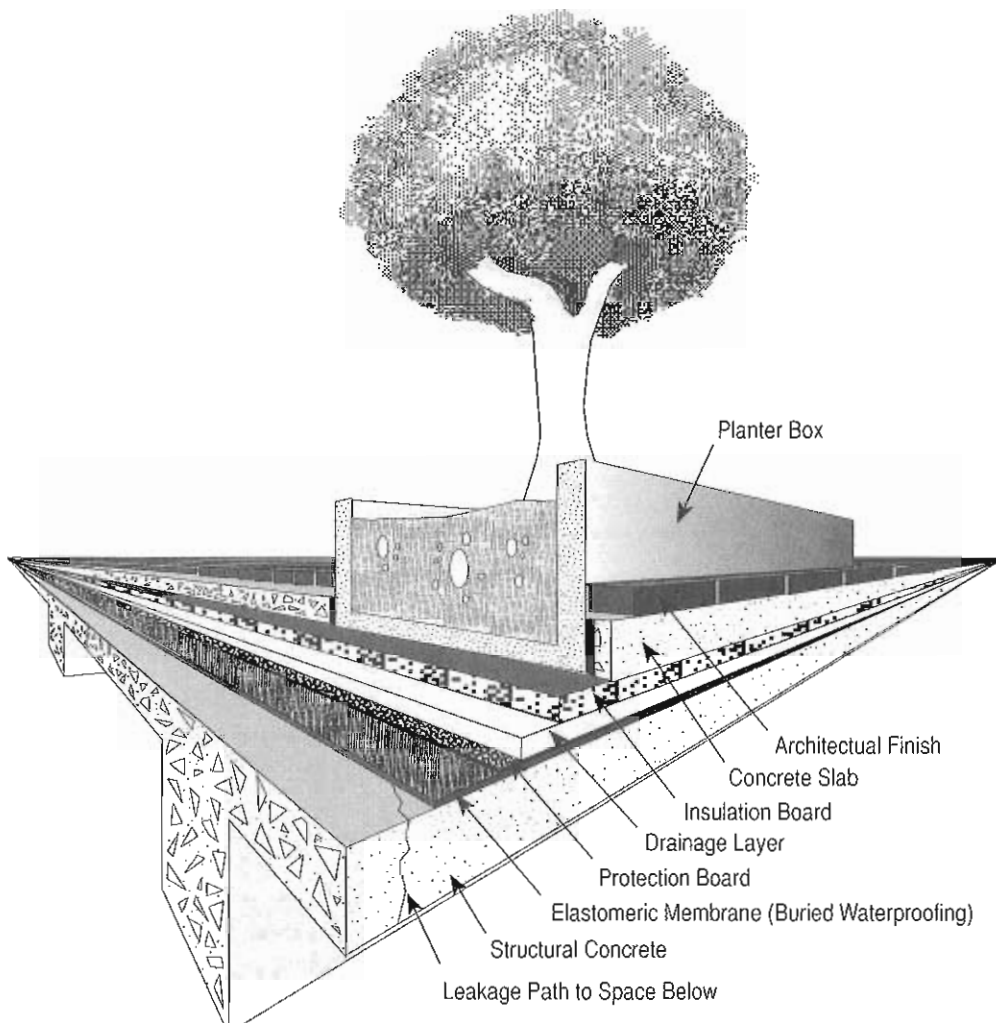
Strategies for Controlling Water Leakage Through Plaza Deck Systems

Construction Methods

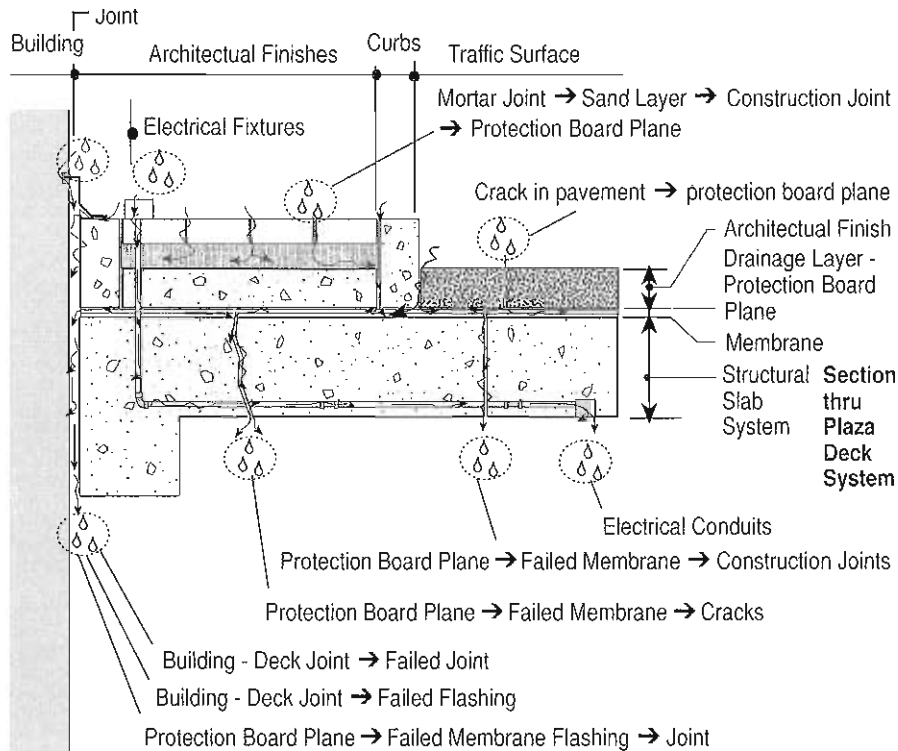
Many plaza deck systems (referring to all systems with buried waterproofing) are troubled with leakage to locations beneath the deck system. These systems are constructed with multiple layers of materials, each of which serves a specific function. The waterproofing system is commonly located directly on the surface of the structural concrete. Leakage may occur beneath

the deck system as a result of deterioration or defects in design and detailing, installation workmanship, or materials associated with the waterproofing system.

Some of the effective waterproofing strategies are presented on the following page. Unfortunately, most effective strategies involve the removal of all surface layers down to the structural slab. This results in substantial cost and interruption of use.



Plaza Deck System



Leakage Paths

Issues and strategies to consider when addressing plaza deck system (buried waterproofing) leakage:

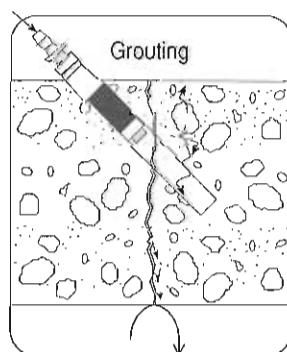
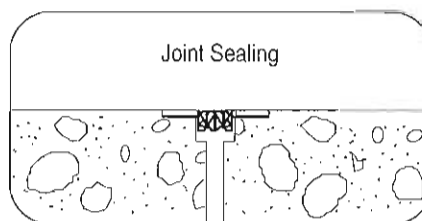
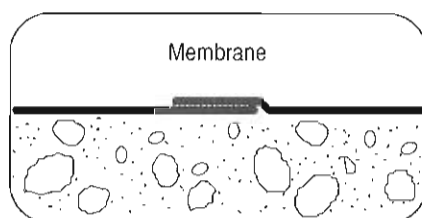
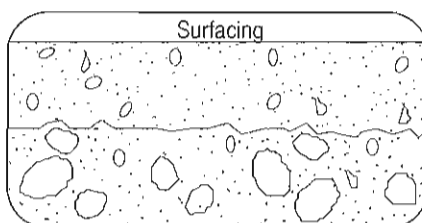
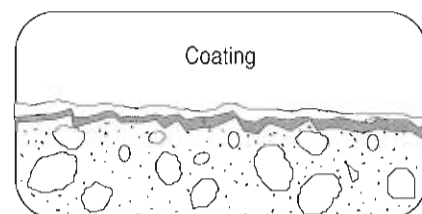
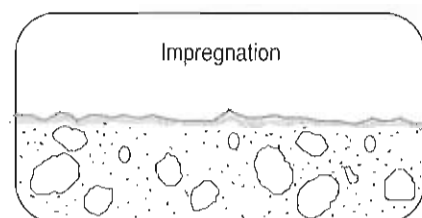
1. Leakage connected with the drainage layer or the protection course will most likely redistribute water to a very large area via the open plane at the drainage level.
2. Leakage through the structural slab may originate from a water source far from the point of leakage.
3. Controlling water flow at the architectural finish level may, at best, only slow down the leakage. Sealing and coating architectural finishes may encapsulate materials in a saturated or high moisture condition, which may lead to failure of the finishes.
4. Controlling water flow through the structural slab system is most directly addressed at the original membrane level. This requires removal of the architectural finishes, drainage layer, protection board, and possibly the membrane.
5. Water that reaches the membrane level should be drained away and not allowed to accumulate.
6. Caution should be exercised when using chemical grouting to stop water leakage. Grouting can affect the function of the drainage system.

Section 2: Methods

The following topics are covered in this section:

Introduction to Methods
Surface Applied Protection:
Impregnation
Surface Applied Protection: Coatings
Surface Applied Protection: Surfacing
(Plastering, Rendering, Overlayment)
Surface Applied Protection: Elastomeric
Membranes (Liquid and Sheet Applied)
Surface Applied Protection: Problems/
Concerns
Surface Applied Protection: Pile
Jacketing
Surface Applied Protection:
Water Control Grouting (Intercept
Penetration)
Surface Applied Protection:
Water Control Grouting (Material
Performance)
Surface Applied Protection:
Water Control Grouting (Positive Side
Penetration)
Surface Applied Protection: Water
Control Grouting (Pipe Joints)
Surface Applied Protection: Joint Seals
(Pressure-Rated Waterstop Joints)
Surface Applied Protection: Joint Seals
(Water Control Rout & Seal)
Surface Applied Protection: Joint Seals
(Load Supporting/Rout & Seal)
Surface Applied Protection: Joint Seals
(Traffic Bearing Expansion Joints)
Altering Electro-Chemical Behavior:
Impressed Current Cathodic Protection

Introduction to Methods



To select a protection method, analyze the strategies discussed in the last section. Many of the protection methods in use utilize an applied barrier which isolates or modifies the aggressive service condition. Isolation and modification of the service condition allows the protected concrete to last longer and/or perform better for the user. Applied barriers is a broad category of coatings, sealers, membranes, joint sealers and injected grout techniques. A summary of each is listed below with a brief description and typical uses:

Impregnation: treatment of a concrete surface with a material which subsequently penetrates into the pore structure. There are three basic types: (1) hydrophobic, (2) partial filling, and (3) filling. Each type of impregnate changes the surface behavior including moisture vapor transmission and liquid absorption. Typical uses of this method include chloride and carbon dioxide screens and protection against freeze-thaw damage.

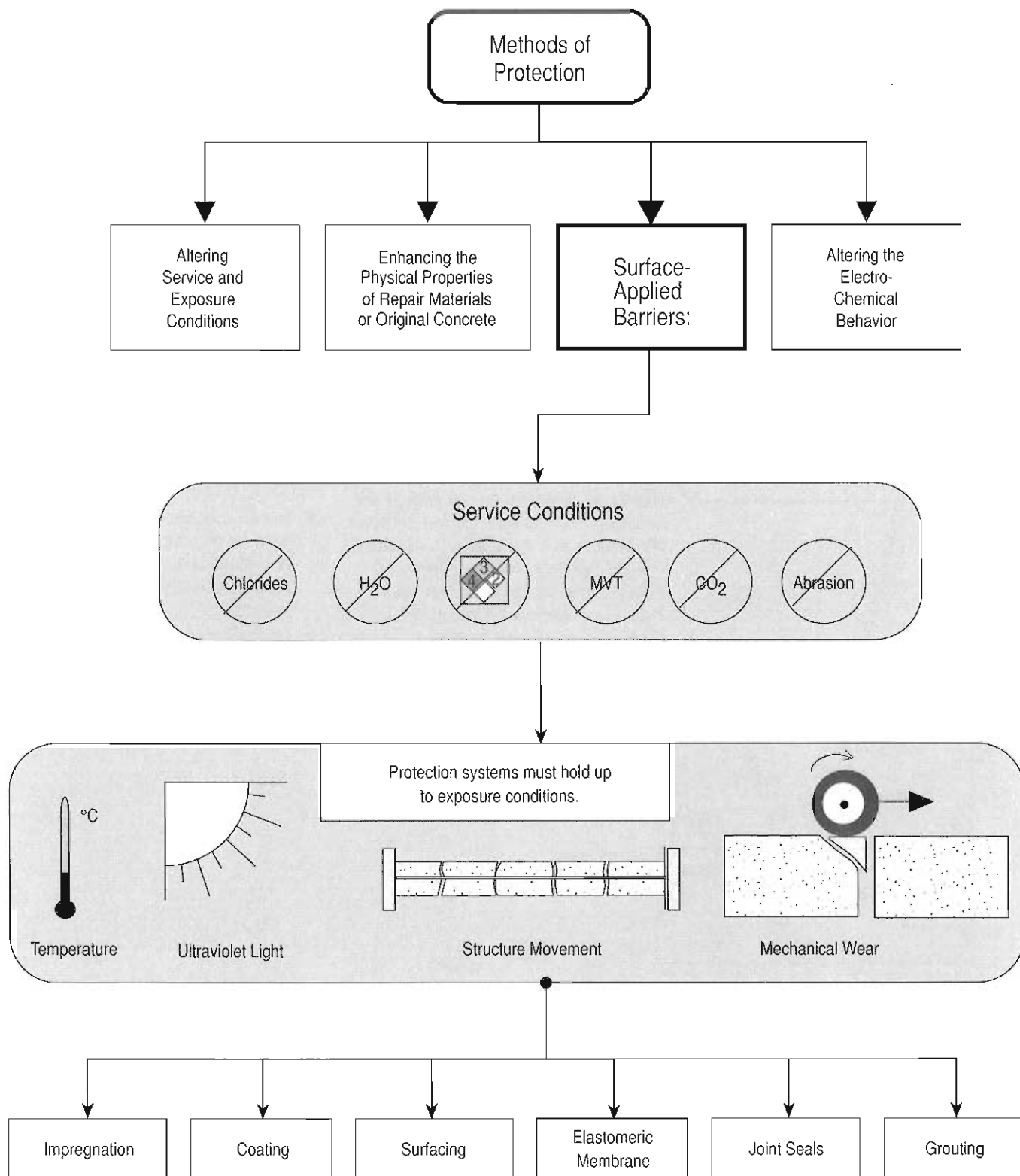
Coating: the process of applying a film-producing material to a concrete surface. Many organic and inorganic coatings are available. Coatings are designed to control water absorption, vapor transmission, and diffusion of aggressive liquids and gasses through the concrete surface. Typical uses include chloride and carbon dioxide barriers, freeze-thaw protection, chemical-resistant barriers and aesthetics.

Surfacing: the process of placing material on a concrete surface to form a uniform, thick layer on that surface. Surfacing is also known as: overlayment, rendering, plastering, or jacketing. Surfacing materials are generally applied by trowel or pneumatically. Surfacing systems are designed to alter moisture vapor transmission, liquid absorption, deteriorating effects of chemicals, flow of surface runoff, energy absorption, and surface texture. Typical applications include: bridge deck overlays, chemical-resistant floors, and carbonation barriers. The effects of reflection of substrate cracking should be considered.

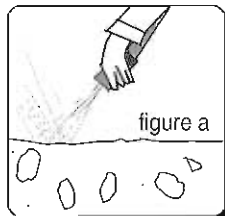
Application of Elastomeric Membranes: the process of placing material on a concrete surface to form an elastomeric film. Elastomeric membranes are either thermosetting liquids, polymer-cured liquids, or preformed materials. The primary function of elastomeric membranes is to minimize liquid absorption by concrete. Elastomeric membranes differ from coatings because of the membrane's ability to move and flex without rupture. Typical applications include: traffic decks, plaza decks, and below grade waterproofing.

Joint Sealing: the process of placing materials into or over an opening within a structure or member to form a barrier to liquid and/or vapor, and/or to absorb/transmit energy and loads. In most cases, joint seals must be able to absorb movement. Typical uses of joint seals include waterproofing of cracks, traffic joints in bridges and parking decks, warehouse floor joints, and waterstops in tanks.

Grouting: the process of injecting materials (grouts) into, behind, or around a structure or member to form a barrier against liquids and/or vapor. Most grout materials solidify to some extent when cured. Grouting barriers are designed to close off passageways within a member or structure. Typical uses include crack and joint waterproofing.



Surface Applied Protection: Impregnation



Preparation of Concrete Surfaces

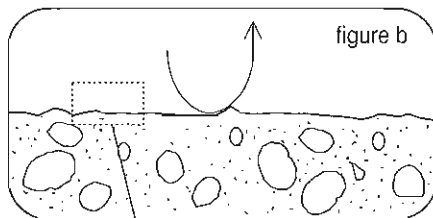


figure b

Protection of concrete surfaces can be accomplished by surface-applied treatments. Impregnation of concrete surfaces is a common technique which is generally used to control the flow of moisture and moisture vapor into and out of concrete. Impregnation techniques require a clean surface capable of absorbing the solutions. Absorption requires open pores and capillaries, which can be achieved with abrasive blasting, hydroblasting, or shotblasting of the concrete surface (Fig. A).

Water repellency of concrete surfaces can be accomplished by lining the pore surfaces with a hydrophobic compound (Fig. C). Silanes and siloxanes are the most common. These compounds are absorbed into the pore structure by suction forces. When silanes or siloxanes are applied to the concrete, a chemical reaction between the sealers and the silicate structure in concrete occurs. They produce an effective barrier against water and aggressive agents infiltration, while allowing water vapor to pass.

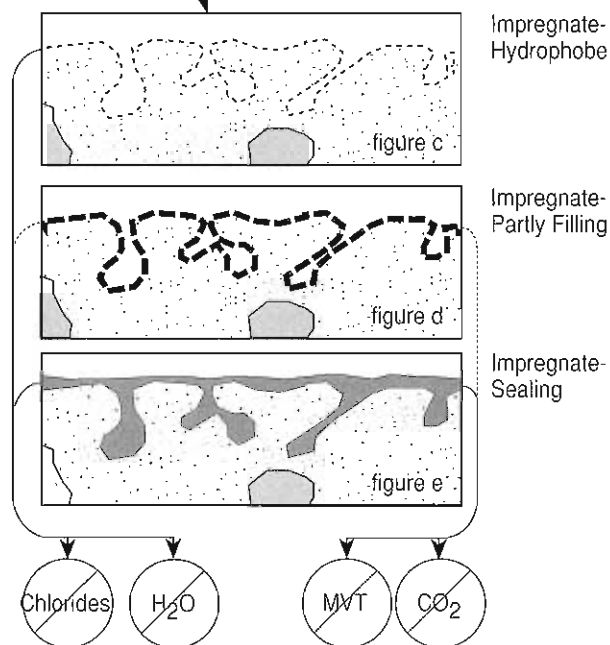
Another method of impregnating the concrete surface involves compounds which are absorbed into the pore structure and fill, or partly fill, the passageways in the concrete (Figs. D & E). There are two types of materials used: first, those which react with the constituents of the cement matrix (such as sodium silicate), and second, those which react and cure on their own (such as low viscosity epoxy, methacrylate, and polyester).

The benefits offered by sealers are:

- increased freeze-thaw resistance.
- reduced infiltration of water and aggressive chemicals, such as chlorides.

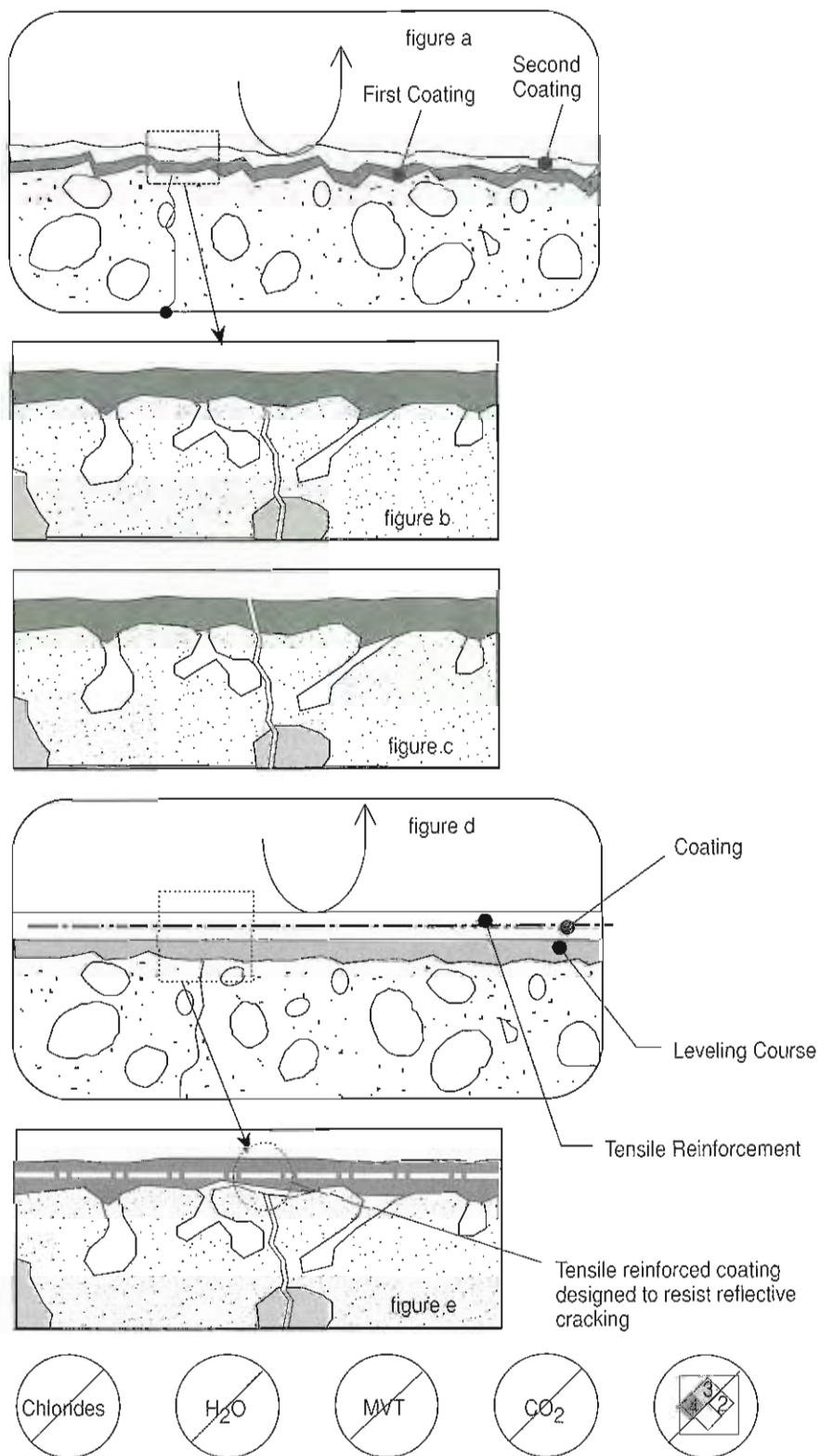
There are a number of caveats that should be attached to the use of concrete sealers:¹

- Not all sealers are equal. A sealer must be chosen carefully on the basis of performance data and applied in accordance with the manufacturer's instructions.
- Verification of the laboratory performance under field conditions is generally lacking.
- Requirements for concrete quality and cover should not be relaxed.



¹Manning, D.G., Durability of Prestressed Concrete Highway Structures, NCHRP Report 140, 1988, Washington, D.C.

Surface Applied Protection: Coatings



Concrete protective coatings include a wide variety of chemicals. Formulations are available to meet various exposure and service conditions. To develop a method and material specification, the following steps should be followed:

1. Determine protection objectives.
2. Determine service and exposure conditions.
3. Determine installation environment.
4. Select materials/system which best meets the service, exposure, and installation conditions.
5. Determine required concrete surface preparation to receive selected repair materials.
6. Determine the range of conditions required by the selected materials.
7. Determine (based on anticipated surface conditions) number of coats or rate of application required to meet required level of continuity. Pinhole-free coatings may require multiple coats.
8. Determine (based on required visible exposed surface textures) any pretreatment required. A leveling course (Fig. D) may be necessary to provide a rough surface with a smooth seamless look after a coating is installed.
9. Determine any crack treatment required.
10. Determine quality assurance methods for surface preparation, bond, thickness, and material quality.

Surface Applied Protection: Surfacing (Plastering, Rendering, Overlayment)

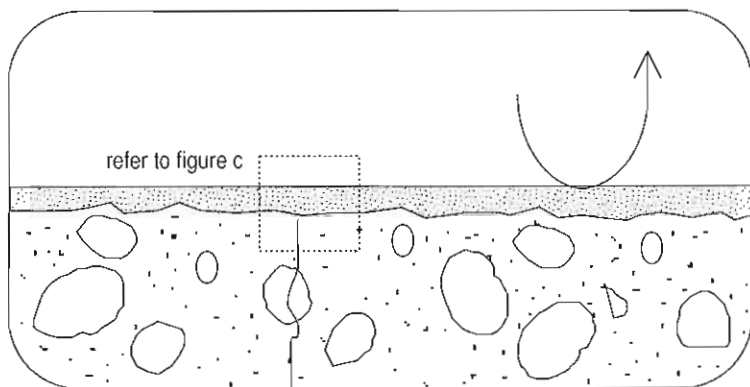


figure a

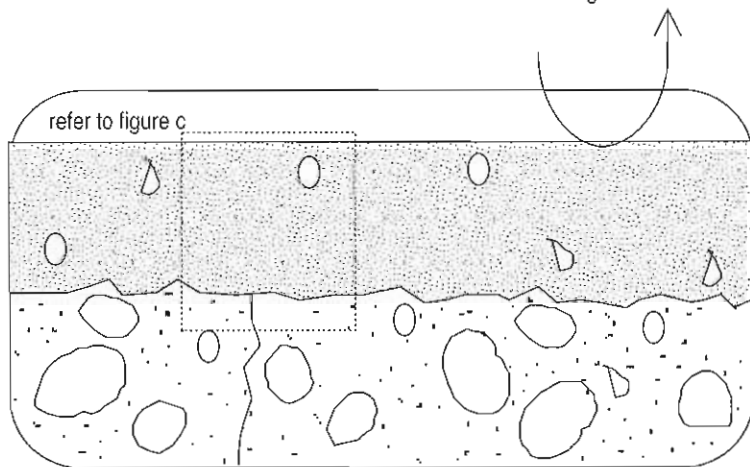


figure b

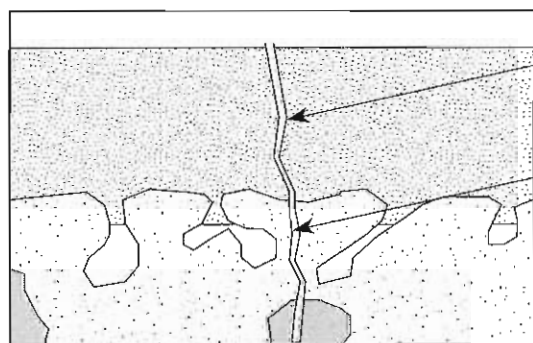


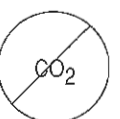
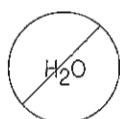
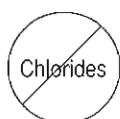
figure c

Surfacing of concrete is a process of placing a relatively thick layer of material to provide protection to the concrete. Various materials and methods of application are used to accomplish different objectives. Common applications and materials include:

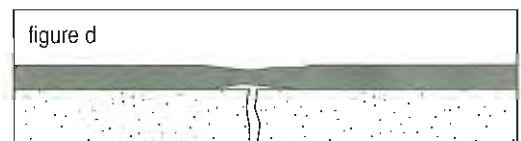
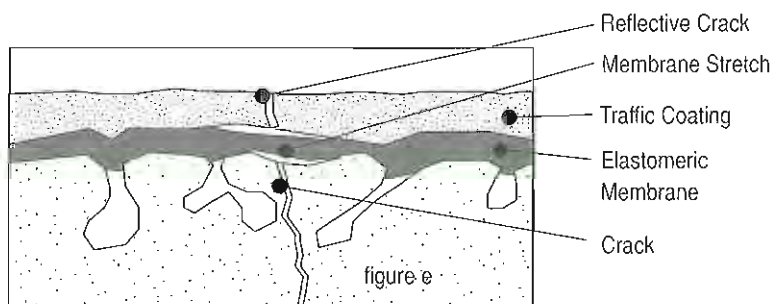
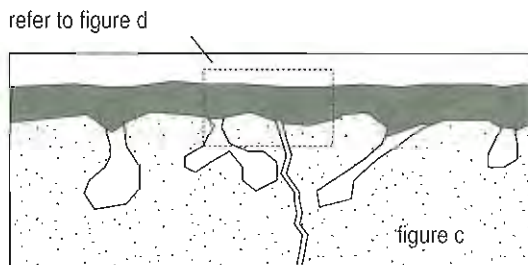
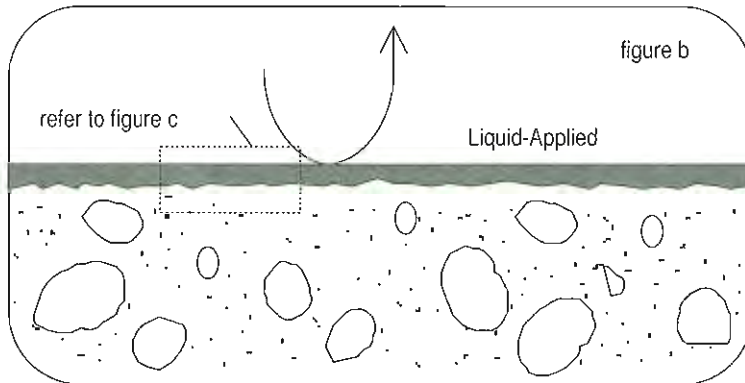
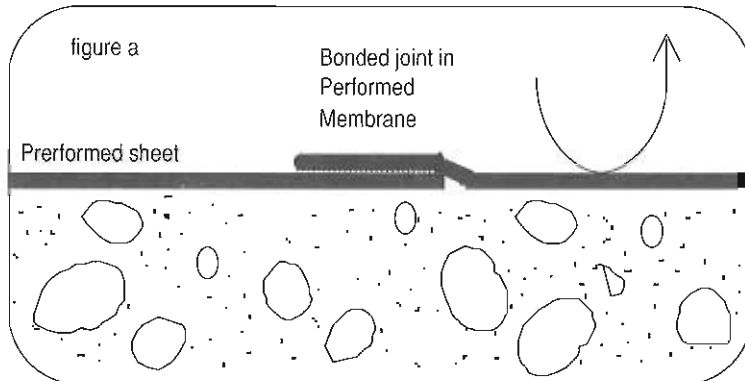
1. Resurfacing industrial floors.
 - epoxy resin/silica sand
 - methacrylate/silica sand
 - steel fiber reinforced portland cement concrete
 - latex-modified portland cement concrete
2. Resurfacing vertical surfaces as a pretreatment to chemical resistant coatings.
 - epoxy resin/silica sand
 - latex-modified portland cement mortar
3. Placing overlays to protect concrete parking and bridge decks from chloride intrusion.
 - latex-modified portland cement concrete
 - latex-modified portland cement mortar
 - layered epoxy resin/broadcast sand
 - microsilica modified portland cement concrete
 - low water/cement (dense) portland cement concrete
4. Redirecting runoff to prevent surface ponding.
 - low water/cement ratio portland cement concrete
 - latex-modified portland cement mortar/concrete
 - milling, sawing, and grinding

Critical considerations for successful installation include:

- compatibility of materials
- bond between the new materials and the existing substrate
- effects of reflective cracking caused by infinite strain (Fig. C)



Surface Applied Protection: Elastomeric Membranes (Liquid and Sheet Applied)



Elastomeric membranes are designed to protect concrete from the intrusion of liquids into or through concrete, cracks and, in some cases, joints. Typical systems used include preformed sheet materials and liquid applied materials.

Preformed sheets include: rubberized asphalt bonded to polyethylene (Fig. A), pvc, neoprene, hypalon, and butyl.

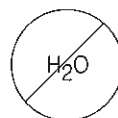
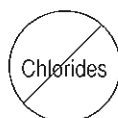
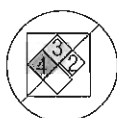
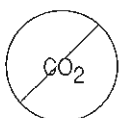
Liquid applied membranes involve in situ placement of materials that are either thermoset, moisture-cured, or two-component chemical-cured. Upon cure, these materials remain elastomeric and form a seamless surface. Specific systems include: hot applied asphalt, neoprene, and polyurethane.

A critical function of elastomeric materials is to bridge moving cracks and/or joints (Figs. C, D).

The ability of a particular material or system to elongate under the anticipated service and exposure conditions is a function of:

1. elongation capability
2. thickness of membrane or,
3. unbonded length of membrane over opening (pretreatment activity).

Some elastomeric membranes are designed to accept pedestrian and vehicular traffic. Many of these systems include a traffic coating which is placed on top of the elastomeric membrane (Fig. E).



Surface Applied Protection: Problems/Concerns

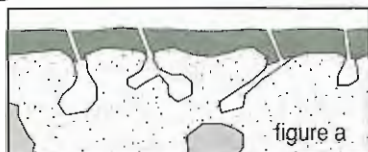
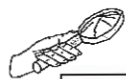


figure a

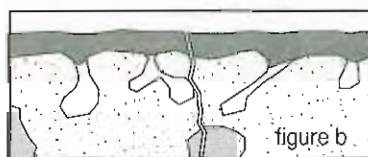


figure b

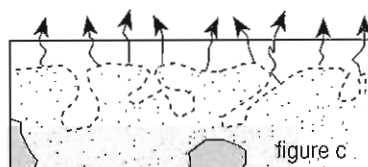


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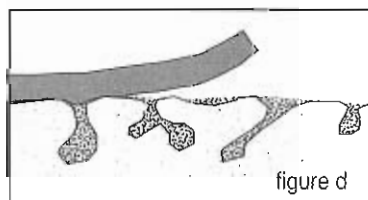


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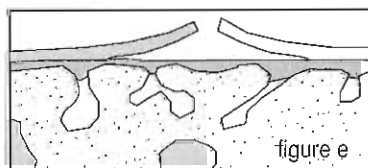


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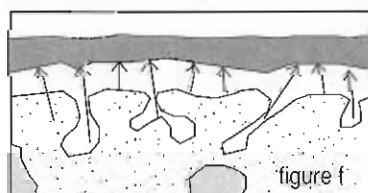


figure f

Pinholes (Fig. A)—Pinholes are caused by movement of gas or moisture vapor through an uncured material. The same factors that cause pinholes may also create blisters. Blisters occur when the gas collects under a partially cured coating, causing the coating to lift off of the substrate in the vicinity of the gas pocket. Controlling pinholes and blisters requires an understanding of the factors that cause movement of gas. A temperature increase during placement may cause gases and moisture within the concrete to expand.

Reflective cracking (Fig. B)—Cracking may occur in a surface-applied material if the material spans a crack or opening which subsequently moves. The movement stresses the spanning surface material. If the surface material is stressed beyond its tensile capacity, rupturing (reflective cracking) will occur. Even materials with large elongation capability may rupture!

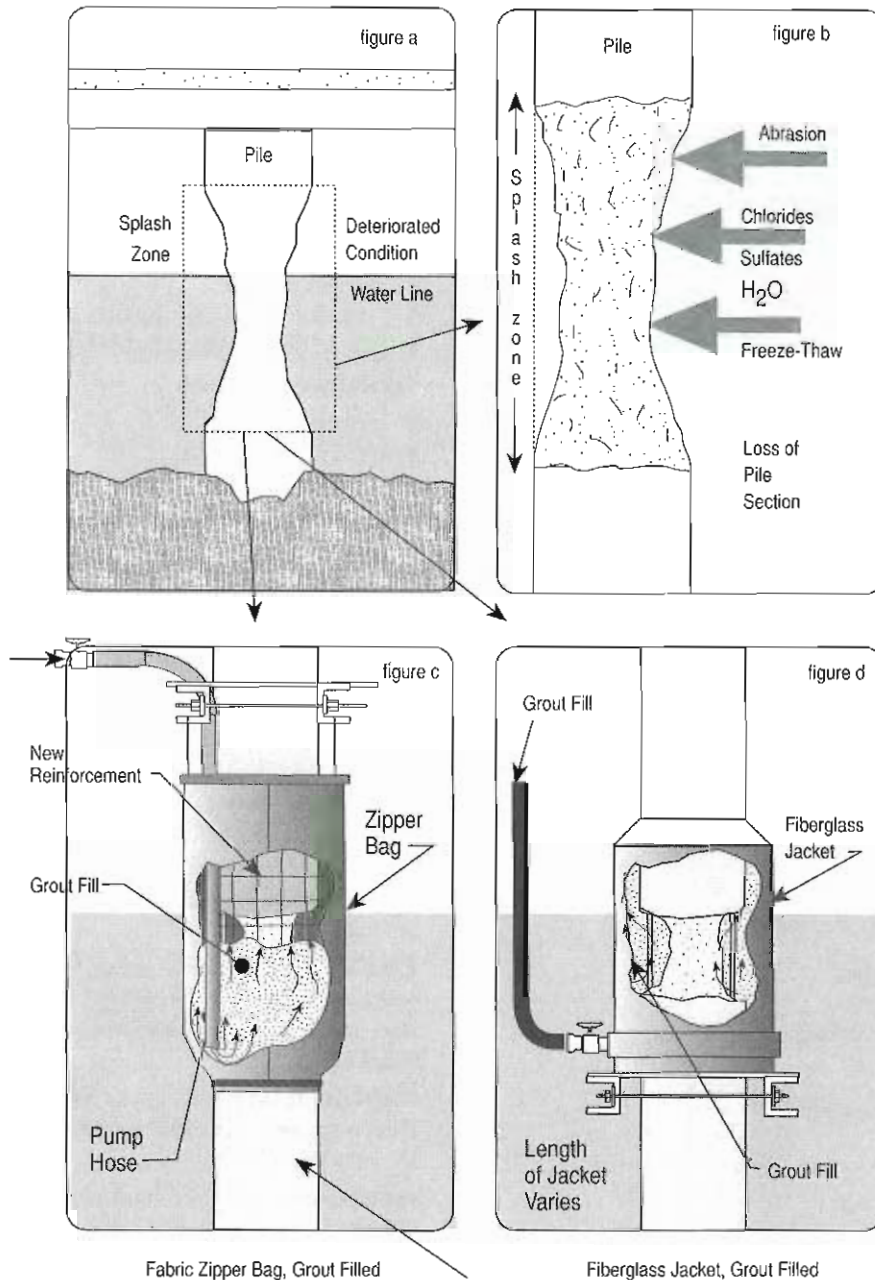
Loss of surface protection (Fig. C)—Surface-applied penetrating sealers with large percentages of volatile carrier may not properly penetrate the surface if wind and temperature conditions cause rapid evaporation during placement.

Debonding (Fig. D)—The durability of surface-applied protection is dependent on the bond with the existing concrete. If surface conditions do not allow for adequate bond, delamination may occur. Typical causes of debonding are poor surface cleaning, water on surface at time of installation, lack of proper priming, and excessive shrinkage of coating material.

Interlayer debonding (Fig. E)—In multi-layer systems, one layer can debond from another. Typical causes are improper time interval between the installation of layers, contamination of a layer, and improper surface preparation of a layer.

Debonding by moisture trapping (Fig. F)—If moisture conditions within the concrete allow moisture to build up beneath the surface protection, pressure sufficient to debond the protection may occur. Moisture build-up can be caused by hydrostatic pressure heads transmitted through the concrete, vapor pressure caused by temperature change, ice crystal growth, or salt crystal formation.

Surface Applied Protection: Pile Jacketing



Alignment of bags around pile may be difficult to maintain in certain situations.

A severe exposure condition for concrete is the tidal or splash zone of fresh, or sea water (Fig. A). In this zone, abrasion, wetting and drying, possible freeze-thaw cycles, and/or aggressive chemicals may result in surface deterioration (Fig. B).

Different surface protection techniques have been developed and many are effective in prolonging the life of repairs and new piles. Fig. C presents a common technique utilizing a porous fabric bag fitted with a zipper. The fabric bag (with the zipper open) is placed around the pile. The zipper is closed and the bottom is drawn tight against the pile surface. Sand-cement grout is pumped into the bag. The porous nature of the fabric allows excess water in the grout to escape while retaining the fines. Jacket installations create an enlarged pile cross-section and extra cover. The extra cover provides a protection system that will not wear away for many years.

The other most common method utilizes a fiberglass jacket as a form for sand-cement grout. Fiberglass remains in place as a protection barrier against the environment. Fiberglass forms come in two types. One type is a one-piece jacket which has a longitudinal seam that allows spreading of the jacket for erection purposes. The other type is a two-piece jacket comprised of two half-round pieces which are erected and fastened together with an interlocking joint. In some instances, the fiberglass is constructed with a small gap between the concrete and the fiberglass. In these installations, epoxy grout is used in lieu of sand-cement grout.

Surface-Applied Protection: Water Control Grouting (Intercept Penetration)

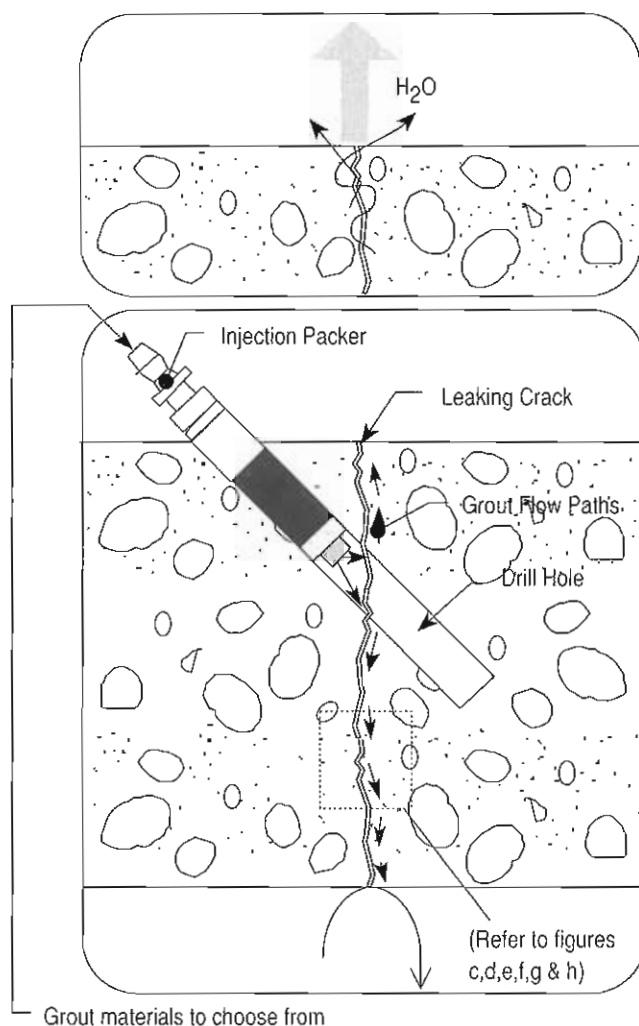
Water leakage entering or exiting a structure may be a significant problem requiring repair. An effective method of reducing, controlling, or eliminating leakage is pressure injecting a material into the passageway between the source of fluid and the leakage point. Materials come in many different forms (see below), and many techniques are available for placement. Successful long-term water control requires an understanding of the variables affecting the installation and operating conditions. Operator skill and experience is critical for overall success.

Condition Variables

- type of fluid
- flow pattern
- pressure head
- temperature
- type of member
- type of passage
- size of passage
- quantity of flow
- condition of passage surfaces
- type of damage/dysfunction occurring

Technique Variables

- grout material
- set time for material
- connection method
- connection spacing
- pressure of material placement
- injection time per connection
- injected volume per connection
- sequence of placement



Grout Materials to Choose From

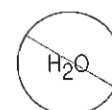
Urethane: hydrophobic, foam or gel resin structure, water reacting, expanding, moderate tensile capacity, moderate viscosity

Urethane: hydrophilic, gel or foam resin structure, water reacting, expanding—low tensile capacity, moderate viscosity

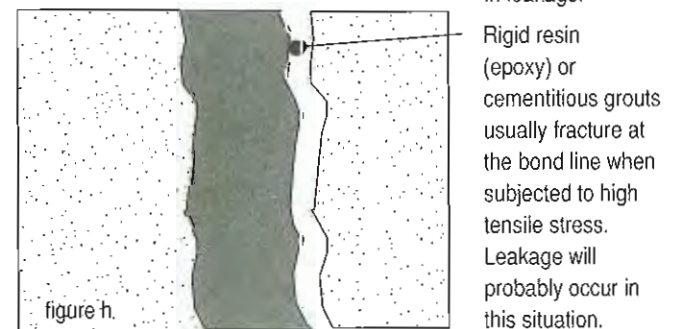
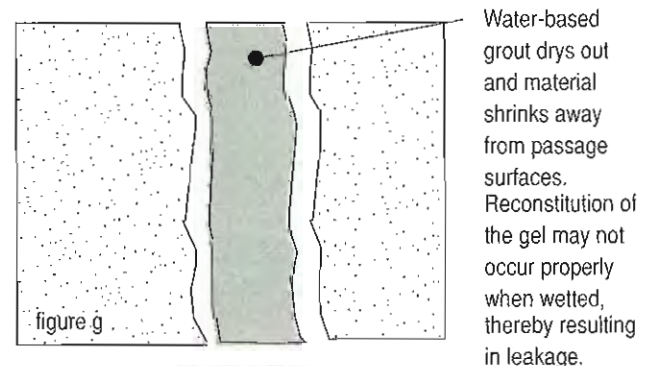
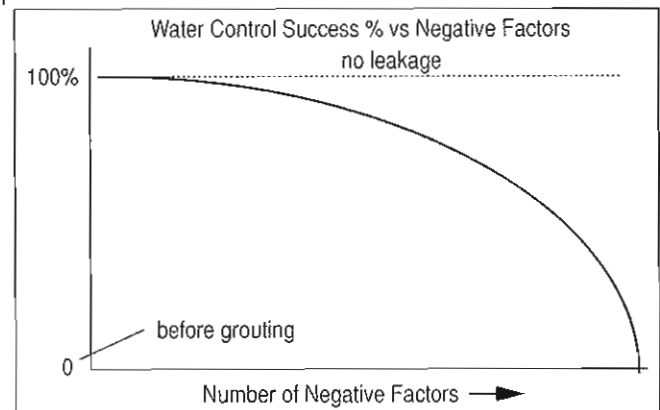
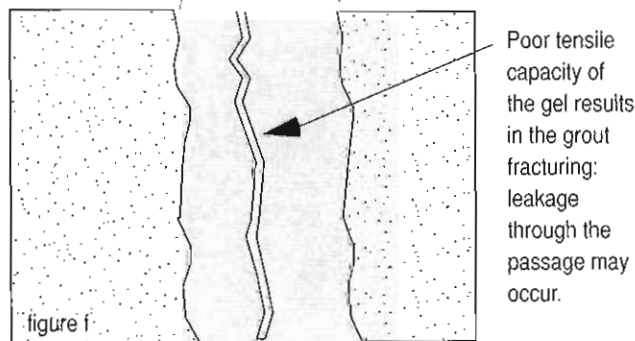
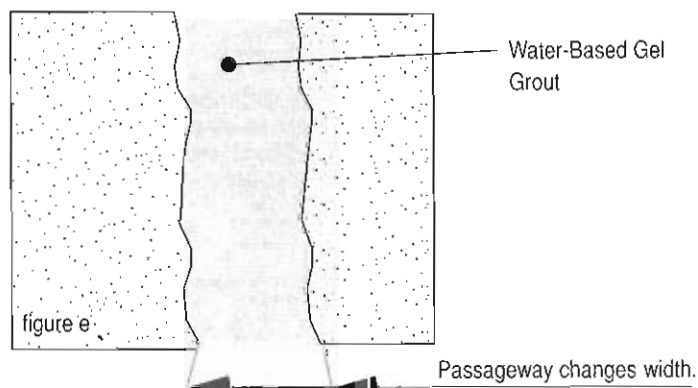
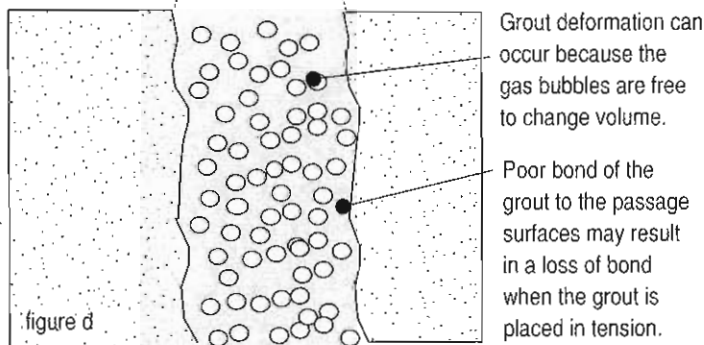
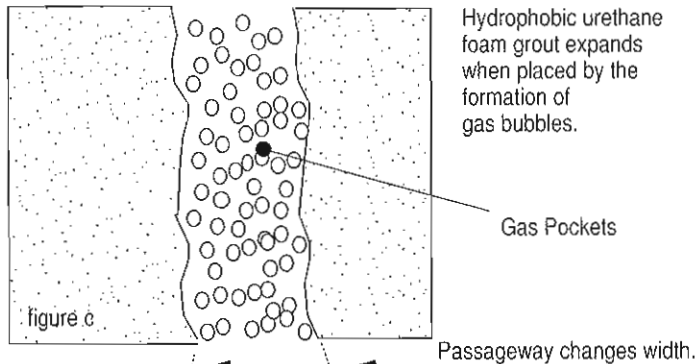
Acrylate: hydrophilic, gel or foam resin structure, very low tensile capacity, very low viscosity

Epoxy: water tolerant, hard plastic, very high tensile capacity, moderate to high viscosity

Microfine cement: hydrophilic, hard cement mortar, moderate tensile capacity, high viscosity



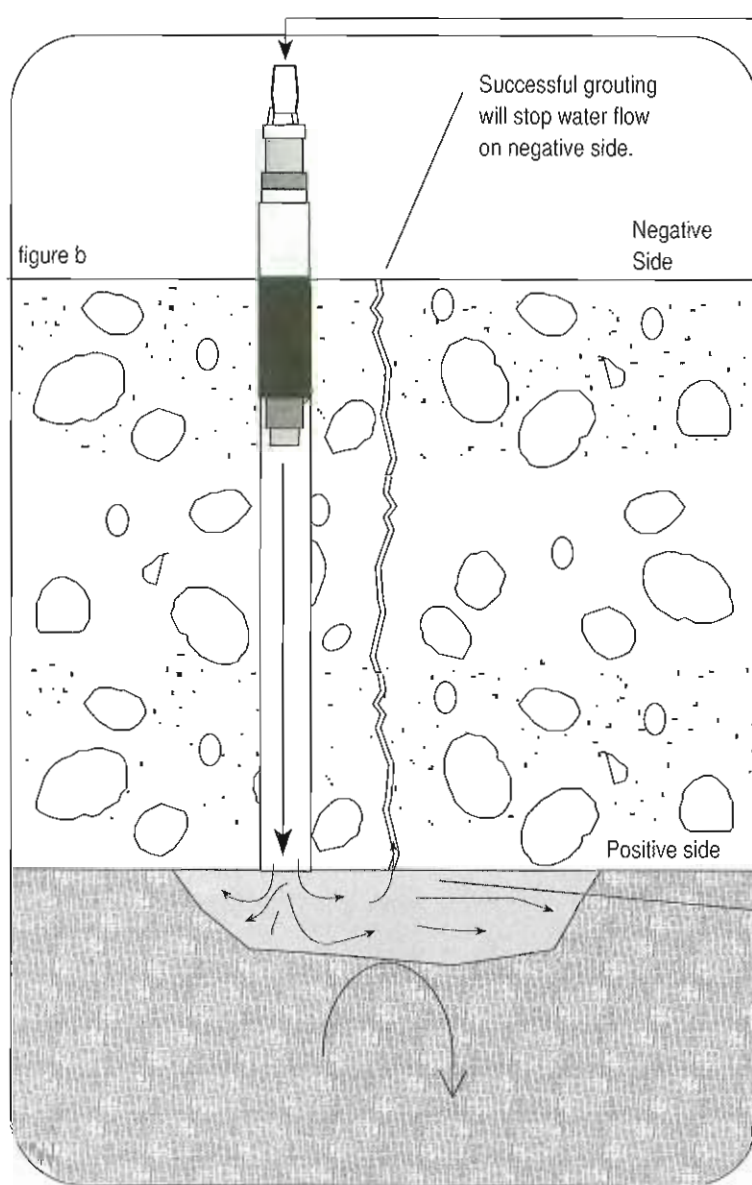
Surface Applied Protection: Water Control Grouting (Material Performance)



Negative factors affecting the long-term water control success

- movement within the passageway
- number of movement cycles
- poor penetration of grout into passage
- freezing of grout material (water-based grout)
- drying out of grout material (water-based grout)
- number of wet/dry cycles
- increase in external fluid pressure
- initial shrinkage of grout material

Surface Applied Protection: Water Control Grouting (Positive Side Penetration)

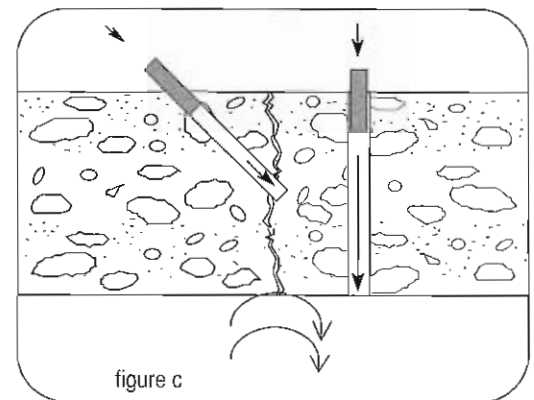


Grout Materials to Choose from

Urethane Gel
Urethane Foam
Acrylate
Type 1 Portland Cement
Cement and Silicate

Micro Fine Cement
Bentonite
Bentonite Cement
Other Polymers

Two Stage Grouting with Positive and Intercept
Techniques Used



Grout flow penetrates the surrounding media (soil), chocking off flow of fluid into passage. The amount of success depends upon the soil conditions. Results maybe uncontrollable.



Surface Applied Protection: Water Control Grouting (Pipe Joints)

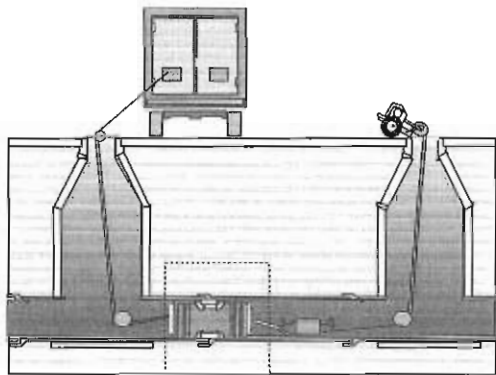


figure a

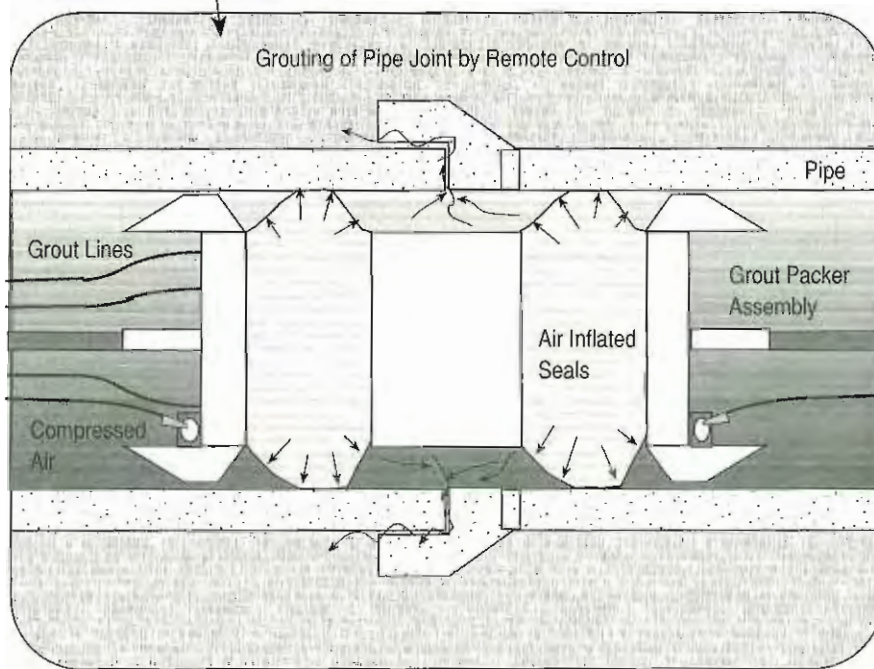


figure b

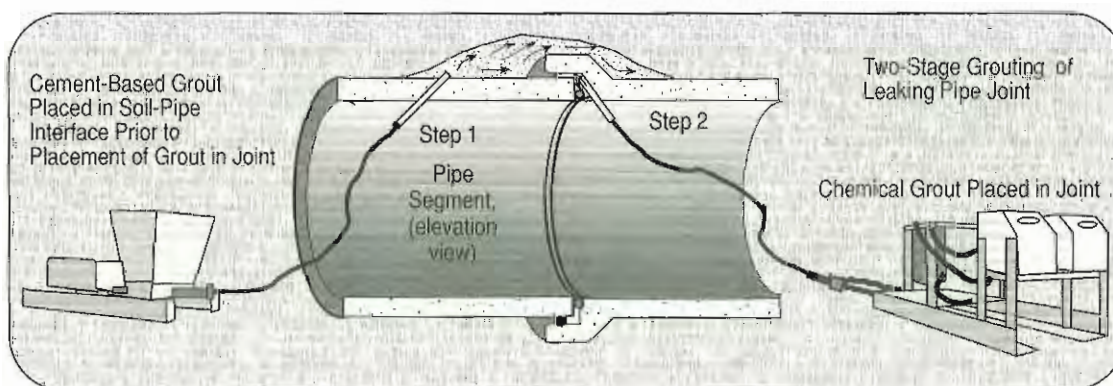
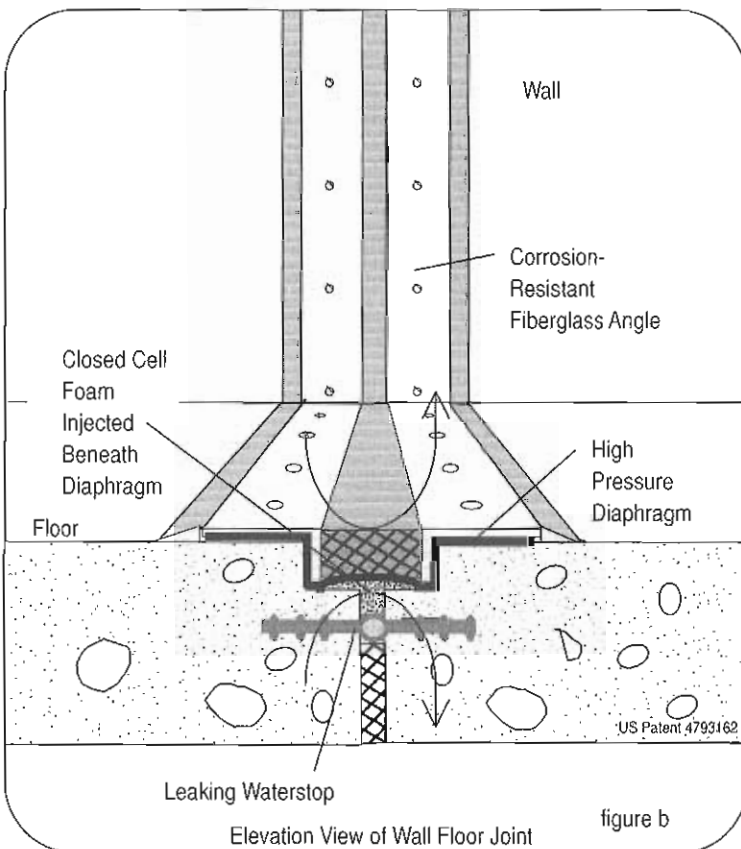
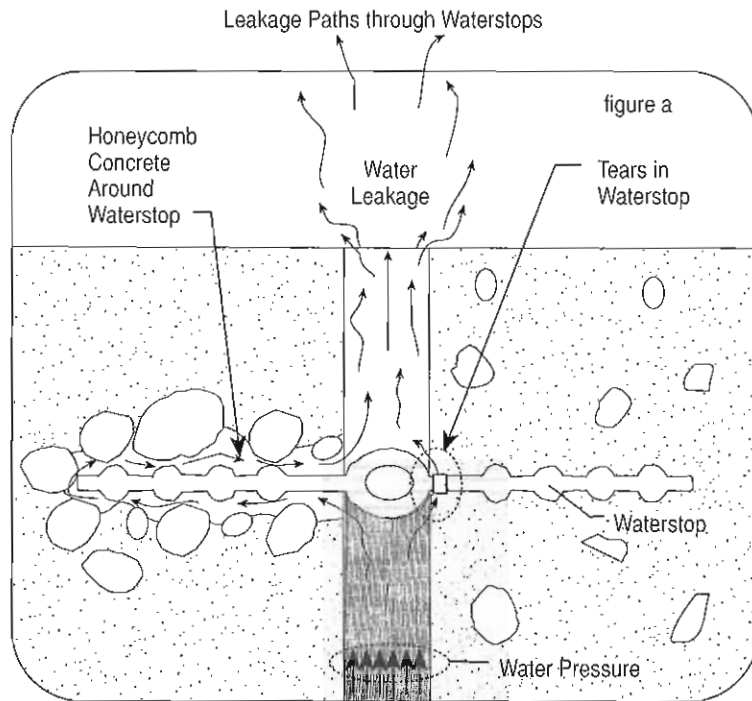


figure c

Pipes are used to transport liquids. Leakage into, or out of, pipes can cause a number of undesirable conditions including: additional liquid in the pipe line, loss of fluid resulting in environmental problems and loss of supporting soil. Pipes can be categorized as either small diameter (workers cannot access) or large diameter (workers can access). Small diameter pipes are repaired using remote controlled equipment (Figs. A, B). Infiltration leaks can be identified using small television cameras pulled through the pipe. Locations are documented, and packers placed at the leaking joint. Chemical grouts are commonly used to stop these kinds of leaks. Alternate methods of pipe repair include the use of an inverted resin felt tube, which is inverted under water pressure and allowed to cure in place, utilizing hot water. The cured-in-place liner acts as a continuous lining, resisting infiltration or exfiltration leakage. Large diameter pipes can be repaired utilizing conventional grouting. Fig. C outlines the repair of a leaking pipe joint and restoration of the lost soil support in the area of the leakage. Cement-based grout is used to fill large cracks in soil and at the soil-pipe interface. Chemical grout is used to seal the leaking pipe joint.

Surface-Applied Protection: Joint Seals (Pressure-Rated Waterstop Joints)

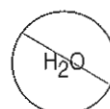


The repair of leaking waterstop joints is a complex process. The original construction of expansion and construction joints utilizes buried waterstop seals, inaccessible for inspection and repair. Identifying the source of leakage is very difficult. Various techniques are available including pressure grouting, bonded rubber sheets, complete reconstruction, or a combination of the above.

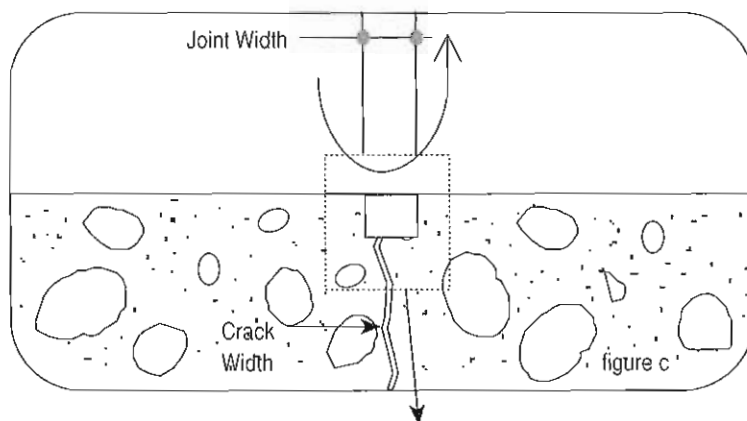
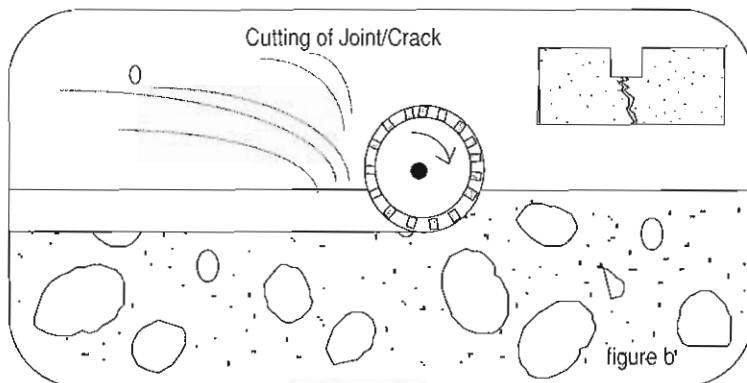
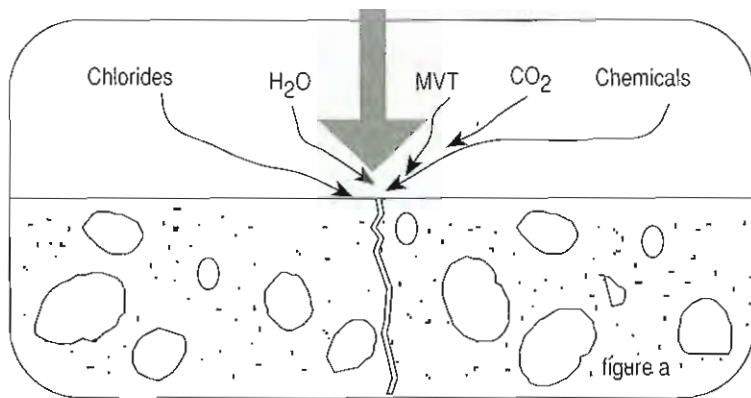
The design factors to be considered are:

- pressure head
- direction of pressure/change in direction
- single direction
- double direction
- movement at joint
- continuity of joint with structure
- type of existing waterstop
- type of suspected defect in existing joint
- width of joint
- longevity of repair required
- access to positive side
- access to negative side

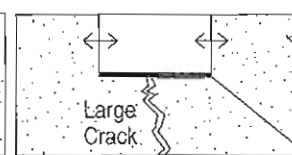
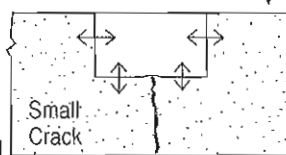
Fig. B shows a combination of systems (proprietary), which includes a high pressure rubber diaphragm sandwiched between fiberglass angles and the concrete surface. A closed cell foam is pressure-injected beneath the diaphragm to protect it and prevent tracking of water. The surface is protected with a prefabricated foam seal. Components are anchored to the concrete with adhesives and mechanical anchors. The system can handle pressure heads in either direction.



Surface Applied Protection: Joint Seals (Water Control Rout & Seal)



Joint seal has three sides bonded if crack width is very small compared to joint width.



Joint seal has two sides bonded if crack is large.

Bond Breaker



Repairing cracks to control access of aggressive fluids and gases is commonly accomplished by the rout and seal method. This method is effective when the source of flow into the crack is from the side that can be routed and sealed (exposed side). Most cracks move with varying loads, temperature, and moisture conditions. Meeting the requirement to make cracks watertight is difficult to achieve with most coating systems, which must cover the cracks. Movement of the crack creates an infinite strain within the coating, and fracturing occurs. The rout and seal technique is useful in conjunction with other protection techniques.

Various tools are used to configure the crack to accept a flush, cured-in-place seal. Grinders, saws, routers, and reciprocating chippers are used to cut the recess (Fig. B). The opening can be cut to different widths and depths, depending upon the performance requirements.

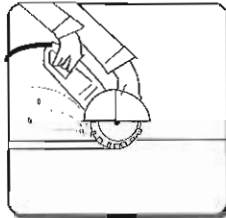
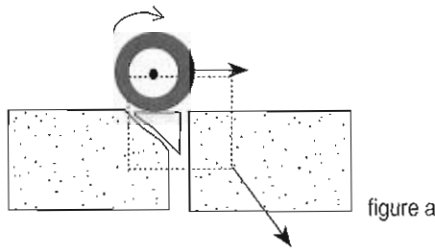
Rout and seal joints can be designed for two-sided or three-sided bond. Narrow cracks with minimal movement may be successfully repaired with three-sides bonded seal (Fig. D). The amount of tensile strain is small compared to the joint width. Usually, crack routing is 3/8" to 1/2" (9mm–13mm) wide.

Materials to choose from:

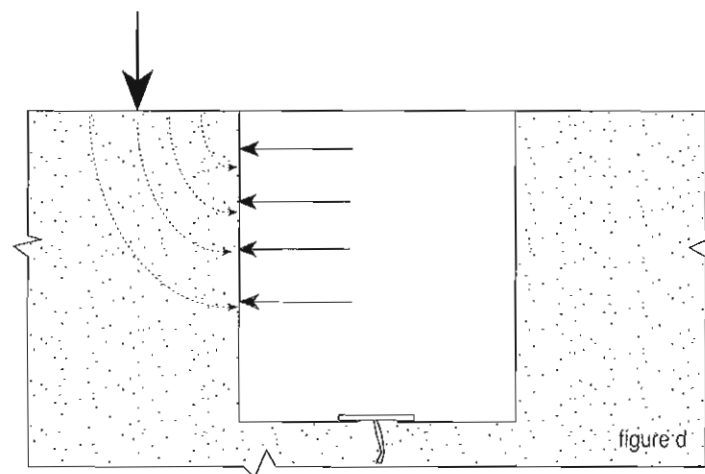
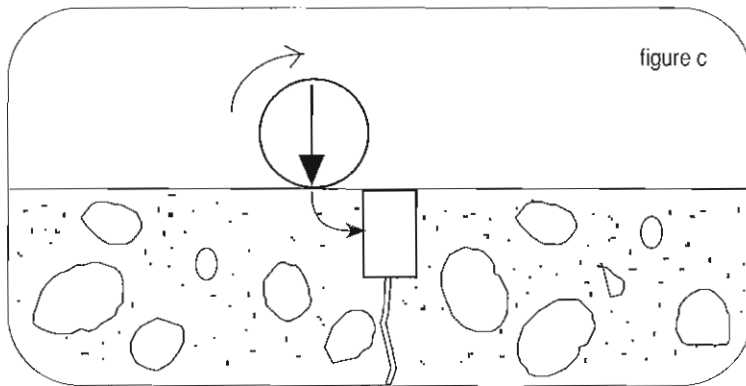
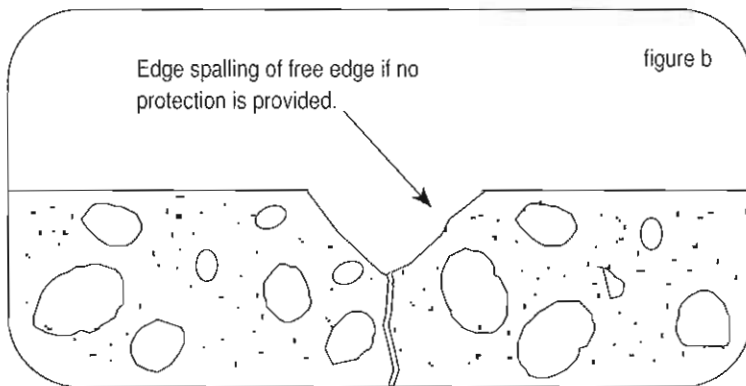
- Silicone
- Urethane elastomers
- Low modulus epoxy
- Polysulfide elastomers

Note: If coatings are to be applied over the joint sealant, poor bond may occur between the coating and the elastomeric sealant, resulting in noticeable exposure of the sealant.

Surface Applied Protection: Joint Seals (Load Supporting/ Rout & Seal)



Preparation of Joint
Opening



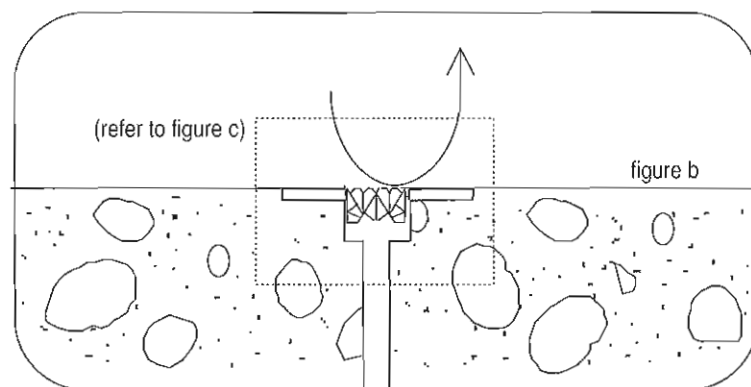
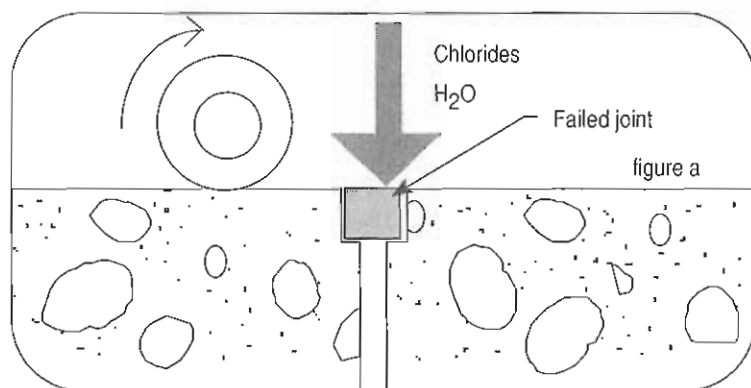
Unsupported joint and crack edges fail from high levels of stress induced by heavy wheel loads and impact (Figs. A, B). Joints in industrial floors are a common location for this type of problem.

Load transfer devices and load carrying sealants in joints protect the free edge from spalling by transmitting and distributing the load stress to the slab areas neighboring the joint. After the load transfer is restored, the joint must be sealed. A typical procedure for installing a load-supporting sealant involves preparation of the free edge by grinding or sawing.

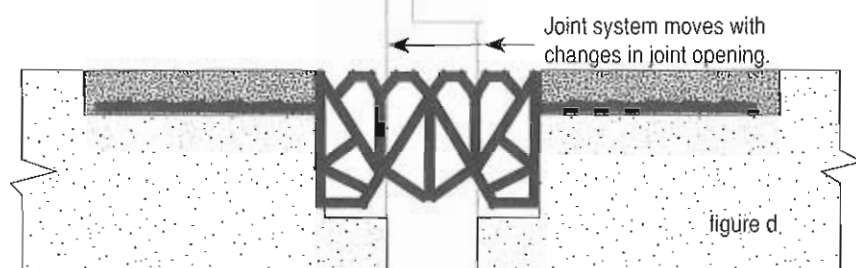
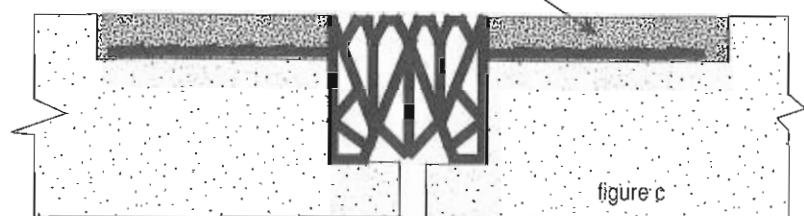
Following preparation, a flexible epoxy resin is placed into the opening, flush with the floor surface. Grinding may be necessary to provide smooth wheel passage over the joint.

Once the opening is protected with a load carrying sealant, the stresses induced by moving wheel loads (Fig. C) will be distributed by load transfer devices and absorbed by the sealant material (Fig. D), thereby reducing the stress level in the concrete below failure levels.

Surface Applied Protection: Joint Seals (Traffic Bearing Expansion Joints)



Polymer nosing is used to absorb impact.
Stress and anchor joint seal to
concrete



Chlorides

H₂O

Expansion joints in traffic-bearing conditions require the following design considerations:

1. Movement at joint
(note: calculate based on field measurements or theoretical thermal coefficient of expansion—approximately 7/8" (22mm) per 100 feet (30.5m) per 100°F (38°C)).
2. Type of traffic duty: pedestrians, cars, trucks, buses.
3. Construction details at joint.
4. Requirement for watertightness.
5. Exposure to snow plows.
6. Connection requirements of other joint systems.
7. Geometric configuration of the joint system.
8. Condition of existing concrete.
9. Aesthetic requirements.

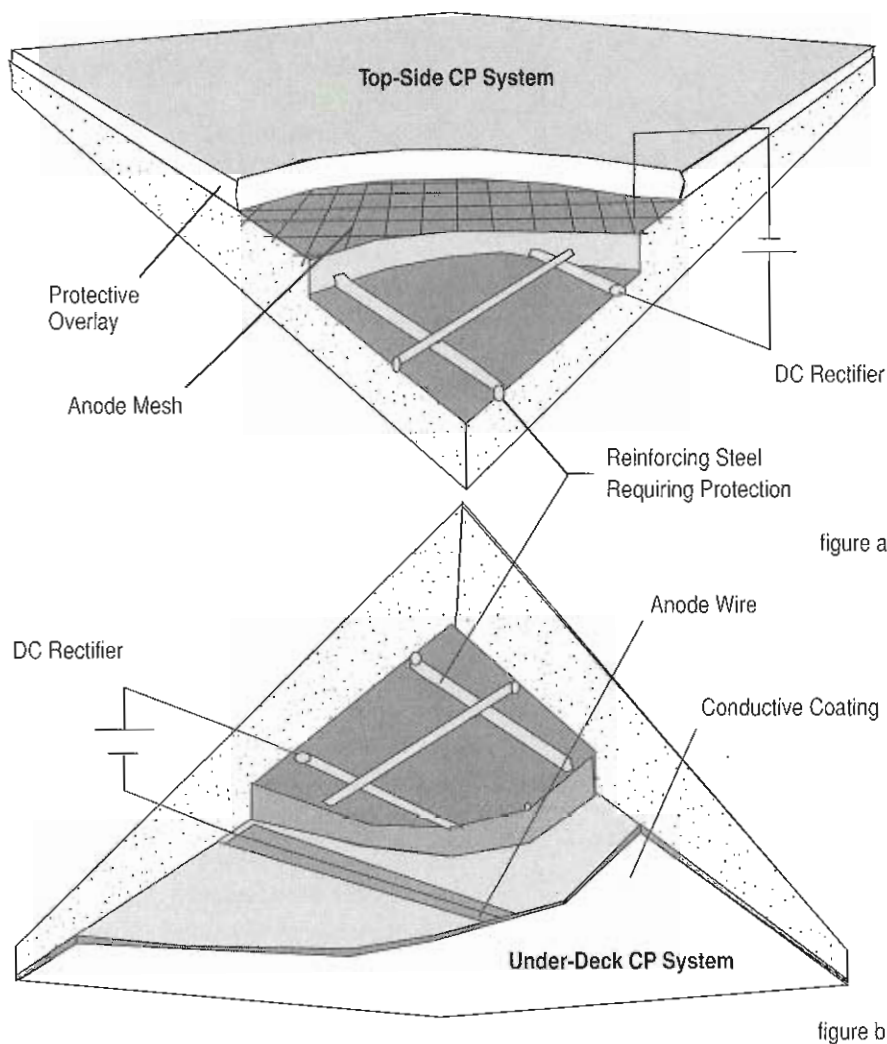
Fig. B and Fig. C outline a typical retrofit joint system. A typical retrofit involves the following steps:

1. Removal of existing joint materials.
2. Reconfiguring joint opening to new system requirements.
3. Repair of deteriorated concrete.
4. Installation of new joint seal.

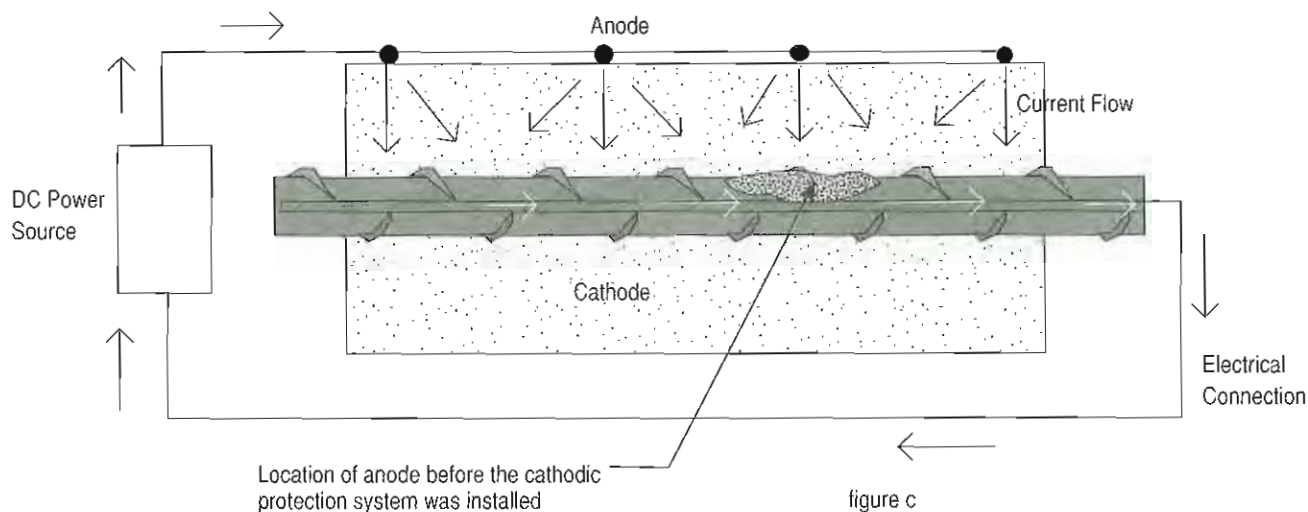
The system shown in Fig. C involves a compression seal designed as a water-stop. The seal has a wing on each side anchored to the concrete with an elastomeric nosing material. The wings help absorb tensile stresses and prevent the flow of water around the conventional compression seal.

Extreme care needs to be exercised when designing connections and splices. Most systems fail in poorly detailed or constructed connections.

Altering Electro-Chemical Behavior: Impressed Current Cathodic Protection



Impressed current cathodic protection (CP) is an electrical process of controlling the corrosion of embedded reinforcing steel. The process involves pumping an electrical current to the reinforcing steel, thus, preventing the bar from corroding (Fig. C). An electrical direct current (DC) volt power source is connected between the reinforcing steel requiring protection and an installed anode system. Electrical power is pumped into the anode system, which distributes the electrical current to the surrounding concrete. The electrical current moves toward the electrically connected reinforcing steel. The concrete between the anode and the reinforcing steel acts as an electrolyte (material capable of transmitting electrical current). In order for the concrete to carry electrical current, adequate moisture levels are required. With top side systems involving protective overlays (Fig. A), it is important that the materials used provide for electrical current flow. All impressed current cathodic protection (CP) systems require constant monitoring and adjustment.



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GLOSSARY

Abrasion	The wearing away of materials by friction. Particles become detached by a combined cutting shearing and tearing action.
Abrasive Resistance	The ability of a surface to resist wear due to rubbing and friction.
Absorption	The process by which a liquid is drawn into and tends to fill permeable pores in a porous solid body; also the increase in weight of a porous solid body resulting from the penetration of a liquid into its permeable pores.
Accelerate	To fasten or quicken the natural progress or process of a reaction or event.
Adhesion	The state in which two surfaces are held together by interfacial forces.
Admixture	A material other than water, aggregates, and cement used as a component of concrete, or mortar, and added to the batch during its mixing.
Air-entraining	The capability of a material or process to develop a system of minute bubbles or air in cement paste, mortar, or concrete.
Air Void	A space in cement paste, mortar, or concrete filled with air, characteristically 1mm or greater in size and irregular in shape.
Alkali-Aggregate Reaction	A chemical reaction in mortar or concrete between alkalis (sodium and potassium) from Portland cement or other sources and certain constituents of some aggregates, under certain conditions. Deleterious expansion of the concrete or mortar may result.
Alkalinity	The condition of having or containing hydroxyl (OH-) ions; containing alkaline substances.
Ambient Temperature	The environmental temperature surrounding the object under construction.
Anode	The positive electrode in a solution of electrolytes where electrons leave the solution, and at which oxidation occurs.
Bleeding	The release of water from the body of fresh concrete or mortar to its surface.
Bond	The adhesion and grip of a material to other surfaces against which it is placed.
Bonding Agent	A substance applied to a suitable substrate to create a bond between it and a succeeding layer.
Bond Breaker	Material used to facilitate independent movement between two units, which would otherwise behave monolithically.
Bond Strength	Resistance to the separation of two materials which are in contact.
Bond Stress	The force per unit area necessary to rupture a bond.
Bracket	An overhanging member projecting from a wall or other body to support the weight acting outside the wall.
Burlap	A coarse fabric of jute, hemp, or flax, for use as a water-retaining cover when curing cementitious materials.
Capillarity	The action by which the surface of a liquid is elevated or depressed when it is in contact with a solid.
Carbonation	The conversion of calcium hydroxide in hardened cementitious material to calcium carbonate by reaction with atmospheric carbon dioxide.
Cathode	The electrode at which chemical reduction occurs.
Cavitation	Pitting of concrete by implosion, i.e., the collapse of vapor bubbles in flowing water which forms in areas of low pressure and collapse as they enter areas of higher pressure.
Chloride Content	The total amount of chloride ions present in concrete or mortar.

Cover	The least distance between the surface of the reinforcement and the outer surface of the concrete.
Coefficient of Thermal Expansion	Changes in linear dimension per unit length, or change in volume per unit volume per degree of temperature change.
Cohesion	The molecular attraction which holds the body of the material.
Cold Joint	A joint or discontinuity formed when a concrete surface hardens before the next batch is placed against it.
Composite	A product made up of different materials.
Compressive Strength	The measured maximum resistance of a concrete or mortar specimen to axial loading.
Consistency	The relative mobility or ability of freshly mixed concrete or mortar to flow; the usual measurements are slump for concrete, flow for mortar, or grout, and penetration resistance for a neat cement paste.
Consolidation	The process whereby the volume of freshly placed mortar or concrete is reduced to the minimum practical space, usually by vibration, centrifugation, tamping, or some combination of these; to mold it within the forms or molds and around embedded parts and reinforcement and eliminate voids other than entrained air.
Corrosion	Degradation of concrete or steel reinforcement by electrochemical or chemical attack.
Corrosion Inhibitor	A chemical compound which, when added in small concentrations to concrete or mortar, effectively checks, decreases, or prevents the reaction of embedded metal with the environment.
Crack	A complete or incomplete separation of concrete into two or more parts, produced by breaking or fracturing.
Creep	The deformation of a body, with time, under constant load.
Curing	The maintenance of humidity and temperature of freshly placed concrete during some definite period following placing, casting, or finishing to assure satisfactory hydration of the cementitious materials and proper hardening of the concrete.
Curling	The distortion of a member that was originally, essentially linear, into a curved shape due to differences in temperature or moisture content in the zones adjacent to its opposing faces.
Deflection	A variation in position or shape of a structure or structural element.
Deformation	A change in dimension or shape due to stress.
Delamination	A separation along a plane parallel to a surface, as in the separation of a coating from a substrate or the layers of a coating from each other; or in the case of a concrete slab, a horizontal splitting, cracking, or separation in a plane roughly parallel to, and generally near, the upper surface.
Deterioration	The disintegration or chemical decomposition of a material during test or service exposure.
Disintegration	Deterioration into small fragments or particles due to any cause.
Drying Shrinkage	Contraction due to moisture loss after cementitious material has been hardened.
Dry Pack	Concrete, mortar, or grout mixtures of dry consistency, usually compacted by ramming.
Durability	The capability of a structure or its components to maintain serviceability over a designed period of time in a specified environment.
Elasticity	The ability of a material to return to its original shape after removal of a load.

Electrolyte	Any substance which, when dissolved in water or other suitable solvent, forms a solution that conducts electricity, the conductivity being due to ionic dissociation of the dissolved substance.
Entrained Air	Microscopic air bubbles intentionally incorporated in mortar or concrete during mixing, usually by the use of surface-active agent, typically between 10 and 1,000 mm in diameter, and spherical or nearly so.
Epoxy Resins	A class of organic chemical bonding systems used in the preparation of special coatings or adhesives for concrete, or as binders in epoxy mortars and concretes.
Erosion	Progressive disintegration of a solid by the abrasive or cavitation action of gases, fluids, or solids in motion.
Exothermic Reaction	A chemical reaction in which heat energy is liberated.
Fatigue	The weakening of a material by repeated or alternating loads.
Feather Edge	The edge of a concrete or mortar placement, such as patching or topping, which is beveled at an acute angle.
Finishing	Leveling, smoothing, compacting, and otherwise treating surfaces of fresh, or recently placed, concrete or mortar to produce a desired appearance and service.
Flexural Strength	A property of a solid which indicates its ability to withstand bending.
Gel	A semi-solid, jelly-like condition of matter. A form of colloidal dispersion in which the dispersed component and dispersing medium are associated to form a jelly-like mass.
Grouting	A process involving the pumping of a liquid of variable viscosity into the soil, fractured rock, or concrete to reduce the permeability of these materials.
Hairline Cracking	Small cracks of random pattern in an exposed concrete surface.
Hardener	A substance that enters into a chemical combination with other substances to form a new, more solid material.
Homogeneity	Uniformity of composition throughout the material.
Hydrophobic	Having no attraction for water.
Impact	The single instantaneous stroke or contact of a moving body with another, either moving or at rest.
Impregnation	A process of filling the interstices of a porous body with polymer compound.
Infiltration	The uncontrolled admittance of air or liquid through cracks and pores in concrete.
Interface	The common boundary surface between two substances.
Jack	A mechanical device used to apply force to prestressing tendons, to adjust the elevation of form supports, and to raise objects.
Joint Sealant	Compressible material used to exclude water and solid foreign materials from joints.
Laitance	A layer of weak and nondurable material containing cement and fines from aggregates, brought to the top of over-wet concrete by bleeding water; the amount of which is generally increased by overworking or over-manipulating concrete at the surface by improper finishing or by job traffic.
Latex	An emulsion of a natural or synthetic rubber in a water phase.
Live Load	Any load that is not permanently applied to the structure.
Matrix	In the case of mortar, the cement paste in which the fine aggregate particles are embedded; in the case of concrete, the mortar in which coarse aggregate particles are embedded.

Membrane	A thin, waterproof barrier consisting of polymeric material which may be prefabricated or applied as a liquid.
Mixture	The assembled, blended, commingled ingredients of mortar, concrete or the like; or the proportions for their assembly.
Modulus	The ratio of stress to strain.
Modulus of Elasticity	The ratio of normal stress to corresponding strain for tensile or compressive stresses below the proportional limit of the material; referred to as <i>elastic modulus</i> or <i>Young's modulus</i> .
Monolithic Concrete	Concrete cast with no joints other than construction joints.
Negative Moment	A condition of flexure in which top fibers of a horizontally placed member, or external fibers of vertically placed member, are subjected to tensile stresses.
Oxidation	The formation of an oxide; the act or process of oxidizing, combining or increasing the proportion of oxygen.
pH (Hydrogen Ion Concentration)	The negative logarithm (to the base 10) of the hydrogen ion concentration of a solution.
Plane of Weakness	The plane along which a body under stress tends to fracture.
Plastic Cracking	Cracking that occurs in the surface of fresh concrete soon after it is placed, and while it is still plastic.
Plastic Shrinkage	Shrinkage that takes place before cement paste, mortar, grout, or concrete sets.
Polymer	A compound formed by the reaction of simple molecules having functional groups, which permit their combination to proceed to high molecular weights under suitable conditions.
Polymer Concrete or Mortar	Concrete or mortar in which a resin serves as a binder.
Porosity	The ratio, usually expressed as a percentage of the volume of voids in a materials, to the total volume of a material, including the voids.
Pop-out	A shallow, corical depression on the surface of concrete.
Pot Life	Storage time interval after mixing, during which a liquid material can be used without difficulty.
Pumped Concrete	Concrete which is transported through hose or pipe by means of a pump.
Quality Assurance	A system of proceeding that ensures that the intended levels of quality on a project are obtained.
Rebound	Aggregate and cement or wet shotcrete that bounces away from a surface against which it is being projected.
Reflection Cracking	The occurrence of cracks in overlays and toppings that coincide with the location of cracks in the base slab.
Relative Humidity	The ratio of the quantity of water vapor actually present to the amount present in a saturated atmosphere at a given temperature, expressed as a percentage.
Restraint	Restriction of free movement of fresh or hardened concrete, mortar, or grout; restraint can be internal and external and may act in one or more directions.
Retardation	A reduction on the rate of hardening or setting, i.e., an increase in the time required to reach initial and final set, or to develop early strength of fresh concrete, mortar, or grout.
Rodding	The compaction of a cementitious material by means of a tamping rod.
Sand Pocket	A zone in concrete or mortar containing sand without cement.

Sawcutting	Cutting of hardened concrete by means of special equipment, utilizing diamond or silicon-carbide blades or discs.
Scaling	Local cracking or peeling away of the surface concrete or mortar.
Settlement	The downward movement of a structure, part of a structure, or underpinning; sinking of solid particles in fresh mortar or concrete after placement and before initial setting.
Shear	An internal force tangential to the plane on which it acts.
Shrinkage	A volume decrease caused by drying and chemical changes.
Silane	A solution of a low molecular weight composition of silicon and hydrogen used as penetrating sealer for concrete surfaces.
Siloxane	A silicon and oxygen-based compound, also containing carbon and hydrogen, used as penetrating sealer for concrete surfaces.
Silica Fume (Microsilica)	Highly reactive pozzolana, a by-product of ferrosilicon production.
Slump	A measure of consistency of freshly mixed concrete equal to the subsidence of the molded, truncated cone immediately after removal of the slump cone.
Soffit	The underside of a member of a building.
Strain	Deformation per unit length.
Stress	Intensity of force per unit area.
Superplasticiser	An admixture that does not alter the surface tension of water; it can be used in low dosages to produce water reduction in concrete or mortar.
Temperature Cracking	Cracking due to tensile failure, caused by a temperature drop in members subject to external restraints; or temperature differential in members subject to internal restraints.
Tendon	A steel element such as wire, cable, bar, rod, or strand used to impart prestress to concrete where the element is tensioned.
Vibration	The energetic agitation of freshly mixed concrete during placing by mechanically oscillating devices at moderately high frequency to assist in its consolidation.
Viscosity	The internal friction resistance of an adhesive to flow when that resistance is directly proportional to the applied force.
Volume Change	An increase or decrease in volume.
Waterstop	A thin sheet of metal, rubber, plastic, or other material inserted in a construction joint to abstract the seeping of water through the joint.
Workability	A property of freshly mixed mortar or concrete which describes its homogeneity and the ease with which it can be mixed, placed, compacted, and finished.

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